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STUDY OF PROPELLANT VALVE LEAKAGE IN A VACUUM

Phase IV Report

10 December 1965 to 14 January 1966

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for

Manned Spacecraft Center
National Aeronautics and Space Administration

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Subject: Phase IV Report - Contract NAS9-4494
Propellant Valve Leakage in a Vacuum

Gentlemen:

Enclosed are twenty-five (25) copies of the Phase IV Report, plus one (1) reproducible copy, concerning the subject contract. The Phase IV Report covers the studies, relating to the Gemini Thruster addendum, which were accomplished during the period Dec. 10, 1965 to January 17, 1966.

Very truly yours,

ATLANTIC RESEARCH CORPORATION

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ALEXANDRIA, VIRGINIA

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1.0 SUMMARY

This report describes the results of an investigation of the adverse effects of evaporative freezing of propellant in the manifolds of the Gemini 25-pound and 100-pound OAMS (Orbit Attitude Maneuvering System) rocket engines. This investigation was added as Phase IV to the original valve leakage program (Contract NAS 9-4494) on December 10, 1965. The investigation consisted of a theoretical analysis of evaporative freezing of propellant in the injector manifolds of the OAMS engines and an experimental study of flow stoppages caused by such freezing in a 25-pound RCS engine (which is nearly identical to a 25-pound OAMS).

The principal results of the investigation are as follows:

(1) As determined experimentally and predicted theoretically, leaking nitrogen tetroxide can freeze evaporatively and obstruct flow in the oxidizer manifolds of OAMS and RCS engines. MMH (monomethylhydrazine), however, cannot.

(2) It was shown experimentally for a 25-pound engine that the residual propellant in the manifold after engine shutdown does not obstruct subsequent propellant flow. This is explained by the fact that the small amount of propellant involved is easily vaporized by the relatively large amount of sensible heat available from the metal parts of the injector. Based on this consideration the same result is predicted for the 100-pound OAMS engines.

(3) In the experiments, the obstructions created by evaporatively frozen nitrogen tetroxide caused either (or both) a delay in the initiation of flow, or (or and) a delay in achieving full flow after the valve was opened. A significant delay of the former type, 16 milsec, was observed only once out of 22 tests. Delays of the latter type were observed in most of the tests, the longest being 552 milsec.

(4) Experimentally, leakage was simulated by rapidly pulsing the solenoid propellant valves. This resulted in a pulsatile flow, which is not characteristic of the normally expected leak. The latter would consist of a trickle flow, and the associated freezing problem is anticipated to be much more severe, including more frequent and longer flow-initiation delays.

(5) Moreover, the pulsatile flow characteristic prevented experimental determination of the range of leak rates, for the normal trickle-type leak, in which evaporative freezing of nitrogen tetroxide can occur within the manifold. However, using the theory that was verified experimentally in Phase I of this program, leak-rate ranges of 0.0033 to 0.131 cc/sec and 0.0035 to 0.62 cc/sec were computed for both the 25-pound and 100-pound OAMS engines, respectively, assuming an initial propellant temperature of 40°F.

Based on these results alone, a recommendation to develop a remedy for propellant freezing and blockage of oxidizer manifolds of the OAMS engines is not justified at this time. The reason is that sufficient data are not available to conclusively establish the seriousness of the effect that such freezing produces on the performance of the Gemini spacecraft. On the one hand, the freezing and blockage may preclude precise control over the firing of the afflicted engine. This is not too serious since compensation is possible through the proper use of the remaining engines. On the other hand, the fuel lead, imposed by a blockage in the oxidizer manifold when an engine is fired, may result in a severe "hard start" once the blockage breaks and flow of oxidizer finally begins. Such an occurrence would be a hazard to both the engine and the spacecraft.

The likelihood and severity of "hard starts" resulting from the blockage of oxidizer flow is not known at present but is scheduled to be investigated in Phase III. Accordingly, there is at present no compelling reason to recommend development of a remedy for propellant freezing in injector manifolds of the Gemini OAMS engines. Further consideration will be given to this once the data from Phase III have been evaluated.

2.0 INTRODUCTION

Several cases of evaporative freezing of propellant have occurred during static test-firings of the Apollo Service Module engine(SPS) in a low-pressure environment. Although the freezing caused no apparent difficulties, an investigation seemed advisable to define the situation more fully. The over-all purpose of this program is (1) to define the conditions for which leakage through the propellant valves will result in freezing and impede proper engine operation; (2) to determine the character and extent of such problems; and (3) to suggest remedial action.

The program was begun June 7, 1965, and was to consist of three phases. Phase I, a study of the effects of leakage of nitrogen tetroxide through a propellant valve into the flow passages of feed and manifold systems, has been completed and the results reported in Reference 3. Phase II, a similar study with Aerozine-50, and Phase III, an investigation of the effects of the freezing of leaked propellant on hypergolic ignition, are to be completed in the near future.

On December 10, 1965, the program was amended to include an immediate five-week investigation of the adverse effects of evaporative freezing of propellant in the manifolds of the Gemini OAMS (Orbit Attitude Maneuvering System) rockets. The successive failure of several OAMS rockets on the Gemini 5 vehicle possibly can be attributed to evaporative freezing of propellant within the injector manifold and the consequent stoppage of propellant flow. Such a situation could involve either the propellant which normally remains in the manifold after engine shutdown, or that which continually seeps into the manifold through leaky valves. This additional investigation, which was designated Phase IV of the over-all program has been completed, and the results are presented in this report. An analysis of the conditions necessary for evaporative freezing to occur and the ability of the frozen propellant to obstruct flow in the 25-pound and 100-pound TCA assemblies is presented in the following section, Section 3.0, Theoretical

Analysis. The results of an experimental investigation of the freezing of leaking and residual propellant in a Gemini 25-pound RCS rocket engine (which is almost identical to a 25-pound OAMS engine) are described in Section 4.0, Experimental Studies. A full description of the test apparatus and procedures is also presented in this section. In the next section, Section 5.0, Conclusions and Recommendations, the significance of the major results are discussed, and recommendations are made for future work. The status of the over-all program is discussed in Section 6.0. Appendix A contains the valid leak test data gathered in the experimental investigation.

3.0 THEORETICAL ANALYSIS

3.1 INTRODUCTION AND CONCLUSIONS

The flow passages of propellant feed and manifold systems of a liquid rocket engine, for a non-firing condition during flight in space, are exposed to a vacuum environment through the engine's injector ports. Any propellant within these passages, arising from valve leakage or the residual after engine shutdown, must undergo evaporation. Because of the very low external pressure, the vapor evolved must pass out through the ports under choked-flow conditions (sonic velocity). Associated with this vapor flow is the removal of the latent heat of vaporization. Consequently, the propellant remaining in the passages cools and, under many conditions, freezes. The latter leads to the accumulation of frozen propellant which may obstruct subsequent propellant flow and preclude the successful refiring of the rocket engine.

The general theory of evaporation and evaporative freezing of propellants and other liquids in a vacuum has been described completely in Reference 1. In the report for Phase I of this program, Reference 3, this theory was applied to the freezing of propellants within the flow passages of propellant manifolds. Quantitative criteria for the occurrence of freezing were derived, and were verified by experiments with nitrogen tetroxide in simulated propellant manifolds. The application of these freezing criteria to the manifold flow passages of the 25-pound and 100-pound TCA engines of the Gemini OAMS gave the following results:

(1) Evaporative freezing of propellant and blockage of the flow passages can occur in the oxidizer feed and manifold systems of both TCA's, but not in the fuel systems.

(2) Such freezing and stoppages will occur only in leakage situations.

(3) Stoppages resulting from the freezing of the residual propellant (dribble volume) after engine shutdown, are very unlikely.

(4) Again for a leakage situation, either nitrogen tetroxide or MMH may evaporatively freeze and accumulate within the combustion chamber of either TCA.

These results are discussed in detail in the following subsections.

3.2 FLOW PASSAGE GEOMETRY AND PLUGGING

The ability of accumulated frozen propellant to obstruct flow through feed and manifold systems depends primarily on the geometry of the flow passages. The flow passages of the Gemini 25-pound and 100-pound TCA engines are described below.

The oxidizer flow passages of the 25-pound TCA consist of a duct 0.34-inch long and 0.05-inch ID beginning at the oxidizer valve seat and terminating at four radial ducts. The radial ducts are approximately 0.13-inch long and have a square cross section, approximately 0.03-inch on a side. These terminate in a single injector port 0.085-inch long and 0.0225-inch ID. The junctions between the main feed duct and the radial ducts, and the radial ducts and the injector ports, form sharp right-angled bends. The fuel flow passages consist of two feed ducts approximately 0.56-inch long and 0.053-inch ID beginning at the valve seat and terminating on opposite sides of a toroidal manifold. The manifold has an approximately square cross section, 0.03-inch on a side, and its circumference is 2.01 inches. Four injector ports, 0.084-inch long and 0.026-inch ID (for the OAMS engines), arise from the manifold at equally spaced intervals. In this case too, the junctions between the feed ducts and the manifold and the manifold and injector ports form right-angled bends.

The corresponding flow passages of the 100-pound TCA are similar. For the oxidizer, the feed duct between the valve seat and the junction with the center of a cylindrical manifold is S-shaped, and has a total length of 1.925-inches and an ID of 0.1 inch. The cylindrical manifold is 0.045-inch high and 0.5 inch in diameter. Sixteen radial ducts 0.037-inch ID and 0.165-inch long connect to the circumference of the cylindrical manifold at equally spaced intervals and terminate at single injector ports, 0.024-inch ID and 0.112-inch long. The junctions between the feed duct and the cylindrical manifold, and the radial ducts and the injector ports are approximately at right angles. The fuel flow passages consist of a single feed duct 1.2-inches long and 0.1-inch ID, which leads from the valve seat into a toroidal manifold. The latter is 1.06-inches in diameter and has an approximately rectangular cross section 0.162-inch by 0.06-inch. Sixteen injector ports, 0.013-inch ID and 0.077-inch long, arise from this manifold at equally spaced intervals. A second toroidal manifold located inside the splash-plate of the injector is connected to the first by a duct 0.16-inch long and 0.06-inch in diameter. The latter manifold is 1.15-inches in diameter and has an approximately square cross-section, 0.092-inch by 0.094-inch. Sixteen radial injector ports, 0.0225-inch in diameter and 0.035-inch long arise from this manifold at equally spaced intervals. The purpose of this latter injector system is to provide film cooling of the walls of the combustion chamber. All junctions between ducts and manifolds, and manifolds and injector ports are at right angles.

Clearly, stoppages within either the fuel or oxidizer flow passages of the two types of TCA are possible in view of the abrupt reductions in cross-section and directional changes from one passage to the next. The presence of right-angled bends and sharp reductions in duct size provides excellent foundations for plugs of frozen material to lodge and resist the pressure of the propellant. The fact that the oxidizer ports are fed by independent ducts, each with a right-angled bend and a reduction in duct size at the junction with its port, indicates that plugging of one or two of the ducts could occur while the others remain unoccluded. As a result, some flow which is less than the designed flow rate would be achieved upon a command to fire. Although freezing also may occur in the injector ports, an effective plug is not formed because the propellants contract upon freezing and cannot obtain a mechanical grip on the smooth walls.

3.3 THE FREEZING OF LEAKING PROPELLANT

As discussed in the report for Phase I, for a leakage situation, the accumulation of evaporatively-frozen propellant within the flow passages of the propellant feed and manifold systems depends on several factors of which the most important are: (1) the geometry of the flow passages and the total area of the injector ports; (2) the physical properties of the propellants, particularly the vapor pressure and temperature of the liquid-solid transition; and (3) the rate of heat transport from the surroundings. Furthermore, as a result of this dependency, it was shown that significant accumulation of frozen propellant can occur only if the leak rate is within a certain range. Since the vapor from propellant within the flow passages can escape only through the injector ports, the rate of heat removal by evaporation is limited by the total area of the ports. It follows, then, that the upper limit of the leak range is defined by the condition that the rate of evaporative heat removal is just sufficient to cool (to the freezing point) and freeze the leaking propellant, and simultaneously remove the heat transported to the frozen propellant from the surroundings. The equation describing this condition is:

$$\dot{M}_{o\,max} = \frac{\left[A_h\, B \frac{P_\sigma\, \Delta H_v}{\sqrt{T_p}}\right] - q_e}{c_1\,(T_o - T_p) + \lambda_f}, \qquad (1)$$

where A_h is the total area of the injector ports, B is a constant which depends on the molecular weight and specific heat ratio of the propellant vapor, ΔH_v is the heat of sublimation, q_e is the rate of heat transport from the surroundings, c_1 is the specific heat of the liquid, λ_f is the heat of fusion, T_o is the initial temperature of the leaking propellant, and P_σ and T_p are the vapor pressure and temperature respectively, at the freezing point (triple-point in the case of a pure substance).

The lower limit of the leak range is defined by the condition that the rate of heat transport from the surroundings is just sufficient to vaporize the propellant as fast as it leaks. That is, there is no accumulation of frozen propellant within the flow passage at leak rates lower than this limiting value. The equations describing this condition are as follows:

$$\dot{M}_o \min = \frac{q_e}{\Delta H_v - (e_l^o - e_s)} \qquad (2a)$$

and

$$\dot{M}_o \min = \frac{B \, A_h \, P_\sigma}{\sqrt{T_s}} \quad , \qquad (2b)$$

where e_l^o is the internal energy of the leaking propellant (liquid), e_s and T_s are the internal energy and temperature respectively, of the propellant within the flow passages, and the remaining symbols have the meanings indicated in the paragraph above.

Application of these equations to the 25-pound TCA engines in the environment of an orbiting Gemini vehicle permits computation of the range of leak-rates for which evaporatively-frozen propellant can accumulate and block the manifold flow passages. Except for q_e, the data needed for this computation are readily available, including the physical and thermal properties of the propellants and the diameters of the injector ports, given above.

The correct value to be used for q_e may be estimated from valve and injector temperature data obtained during the flight of Gemini 7. Under nonfiring conditions the injector temperature (actually the metal plate enclosing the back of the engine) was approximately 50°F. The temperature of oxidizer valve was generally in the range of 70°F to 80°F. The valve is warmed by a 1.25-watt heater used to prevent severe cooling by thermal radiation (indirectly) into space. As an additional safety feature, a second 1.25-watt heater is available and turns on automatically if the valve temperature drops below 20°F. Based upon these facts, and considering the available paths for thermal conduction between the oxidizer valve and the injector plate, it was determined that the appropriate value of q_e is 1.25 watts for leakage of both nitrogen tetroxide and MMH (monomethylhydrazine).

For the 100-pound TCA, no temperature data exist. However, the same heater arrangement on the oxidizer valve is used and therefore it is reasonable to assume the same value for q_e.

The maximum and minimum leak rate values, computed on this basis using Equations (1) and (2) for nitrogen tetroxide at selected initial temperatures in both the 25-pound and 100-pound TCA, are listed in Table 3-1 and shown graphically in Figures 3-1 and 3-2. For MMH, the rate of evaporation from the frozen propellant within the fuel flow passages is such that the rate of heat removal associated with the vapor flow is less than 1.25 watts. Accordingly, MMH may cool evaporatively to a low temperature but cannot freeze and plug the flow passages.

Just as evaporatively frozen propellant can accumulate in the manifolds, it also can accumulate within the combustion chamber. The maximum leak rate for this occurrence is determined by the rate of vapor flow through the throat of the nozzle. Accordingly, Equation (1) applies to this case when the area of the throat is substituted for A_h. Since the combustion chambers of the Gemini TCA's are well insulated, q_e may be assumed to be zero. Assuming an initial propellant temperature of 40°F, the maximum leak rate values of nitrogen tetroxide within the combustion chamber are 7.35 and 33.9 cc/sec for the 25-pound and 100-pound TCA, respectively. The corresponding values for MMH at the same initial temperature are 0.0084 and 0.042 cc/sec.

3.4 FREEZING OF RESIDUAL PROPELLANT AFTER ENGINE SHUTDOWN

Although the residual volume of propellant which is contained within the feed and manifold flow passages after engine shutdown, may freeze, it is unlikely that a flow stoppage will be created by this

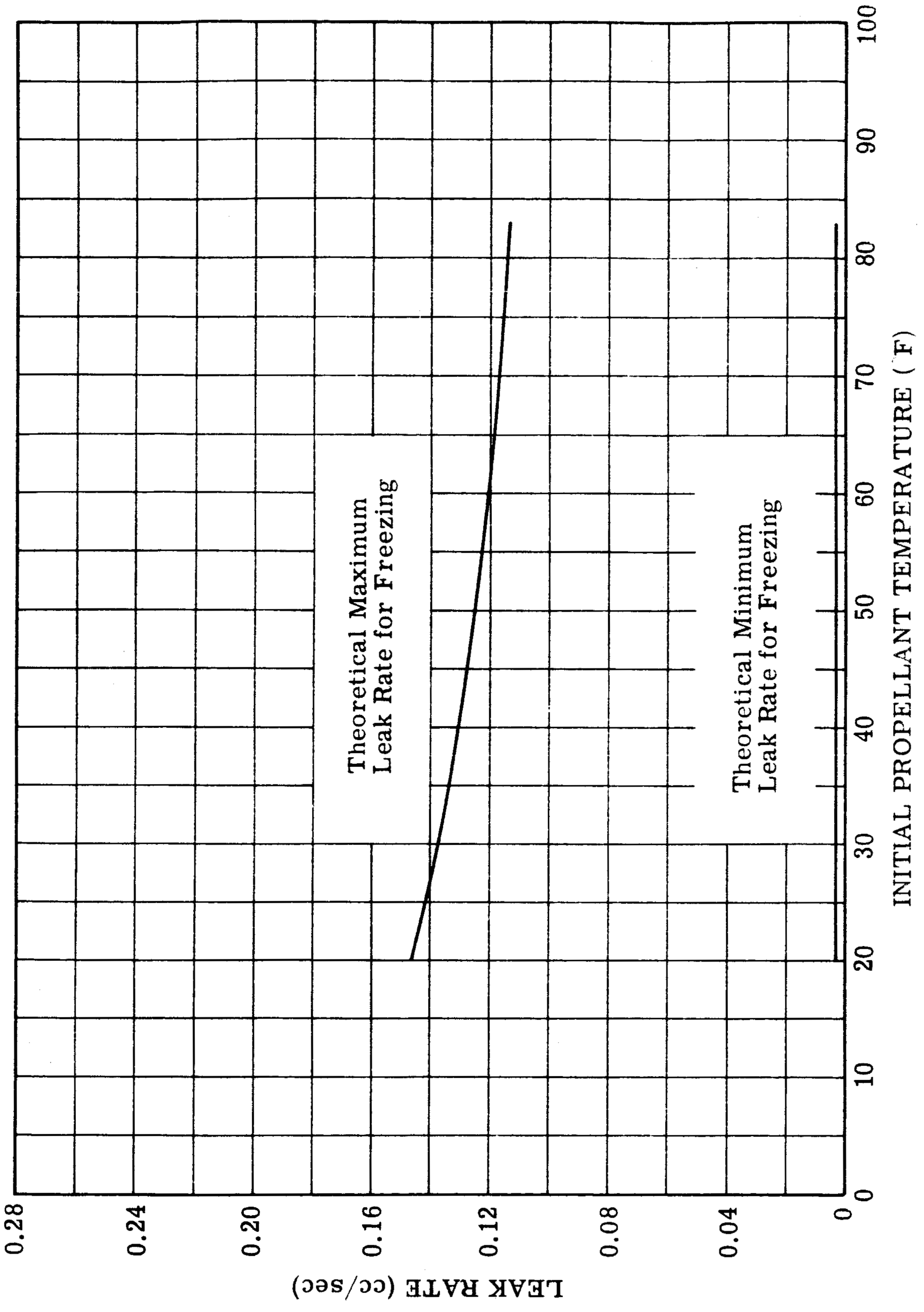

Figure 3.1. Calculated Leak Rate Range for the Accumulation of Frozen Nitrogen Tetroxide Within the Manifold of a Gemini OAMS 25-Pound TCA.

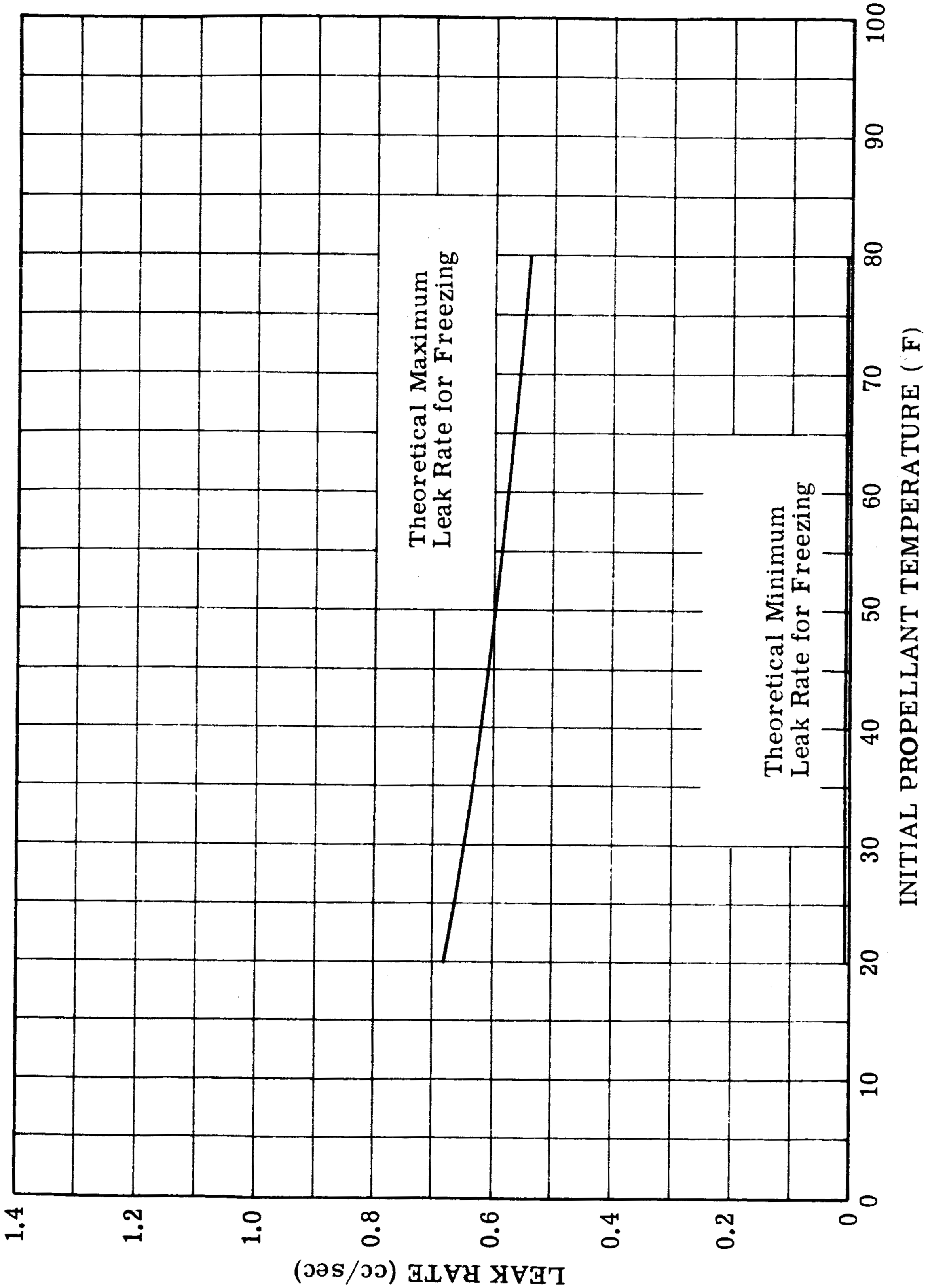

Figure 3-2. Calculated Leak Rate Range for the Accumulation of Frozen Nitrogen Tetroxide Within the Manifold of a Gemini OAMS 100-Pound TCA.

TABLE 3-1

THE LEAK-RATE RANGE FOR THE ACCUMULATION OF FROZEN NITROGEN TETROXIDE WITHIN THE OXIDIZER FLOW PASSAGES OF THE GEMINI OAMS ENGINES

Initial Propellant Temperature (°F)	Leak Rate Values (cc/sec) 25-Pound TCA Minimum	25-Pound TCA Maximum	100-Pound TCA Minimum	100-Pound TCA Maximum
20	0.0030	0.146	0.0033	0.68
40	0.0033	0.131	0.0035	0.62
80	0.0038	0.114	0.0042	0.54

occurrence except perhaps for a very brief span of time. This is especially true if the engine had become very warm during firing. The reason for this is that the maximum volume (the total volume of the flow passages) of the residual propellant is small and requires a minimum of heat for complete vaporization. For the 25-pound TCA these maximum volumes of nitrogen tetroxide and MMH are 0.00243 and 0.00483 in^3, respectively. The heat required to vaporize these volumes corresponds to the heat content in the injector plate for temperature changes of only 0.9°F and 3.2°F, respectively. For the 100-pound TCA the corresponding volumes and temperature changes of the injector are 0.00297 and 0.00742 in^3, and 4.7 and 19.8°F, respectively. Actually, the amount of residual propellant and the heat required for complete vaporization most likely will be much less than these maximum values. This is because the propellant will boil within the flow passages, and much of the liquid will be expelled through the injector ports by the growing vapor bubbles.

4.0 EXPERIMENTAL STUDIES

4.1 DISCUSSION

The purpose of the overall experimental program is to investigate propellant leakage through propellant valves and determine the extent of plugging of propellant flow passages and attendant flow delays produced by evaporative cooling and freezing of propellants. The original test program was divided into three phases and was concerned with ball-type propellant valves similar to those used on the Apollo SPS engine. As was stated in Section 2.0, the Gemini work became Phase IV of the program and was scheduled to be performed during a period of approximately five weeks starting December 10, 1965. Accordingly, the effort on Phase II was temporarily suspended while the Phase IV tasks were accomplished.

The Gemini tests have been completed and this report delineates the accomplishments achieved during Phase IV. A total of 53 tests were conducted: 46 using nitrogen tetroxide as the test medium, and 7 using monomethylhydrazine (MMH) as the test medium. Three types of tests were conducted with each propellant:

1. Flow without leakage to determine the "baseline" flow delay not attributable to stoppage by freezing (14 tests with N_2O_4 and 3 tests with MMH).
2. Engine shutdown tests to determine flow delays because of the residual propellant (dribble volume) freezing between the propellant valve and injector (10 tests with N_2O_4 and one test with MMH).
3. Valve-leak tests to determine flow delay caused by propellant freezing during the interim between firings of the engine (22 tests with N_2O_4 and three tests with MMH).

The results of these tests can be summarized as follows:

1. Leakage of N_2O_4 through the propellant valve can result in evaporative freezing and blockage of the flow passages.
2. A <u>flow-initiation</u> delay of 16 milliseconds and <u>full-flow delays</u> up to 552 milliseconds were experienced as a

result of freezing of N_2O_4.

3. At the higher leak rates, frozen N_2O_4 appeared to fill the combustion chamber, and frozen N_2O_4 was extruded through the nozzle during some tests.
4. After the N_2O_4 valve was closed at the end of a leak test, injector temperatures usually dropped below 0°F, and in one case dropped to -36°F.
5. No flow delays were detected during the dribble volume tests.
6. No freezing or flow delays were noted during the MMH tests.
7. After the MMH valve was closed at the end of a leak test, very little change was noted in injector temperature.

4.2 TEST APPARATUS

4.2.1 High Altitude Facility

The major tool used in performing the experiments is the Atlantic Research Corporation high altitude tunnel facility. Figure 4-1 depicts this facility and some of the pertinent characteristics.

Briefly, the test chamber of the facility consists of a cylindrical stainless steel tunnel, 6 feet in diameter and 25 feet long, which is exhausted by a 5 stage steam ejector system. The facility has a design pumping capacity of 71,000 liters of air per second at a pressure of 0.06 torr and a no-load minimum pressure capability of 0.02 torr, which simulates an altitude of approximately 245,000 feet. This provides adequate simulation of the vacuum of the space environment in this case, since the triple-point pressures of pure N_2O_4 and pure MMH are approximately 140 and 0.106 torr, respectively (see discussion in Section 3.0).

4.2.2 Propellant Flow System

The N_2O_4 and Aerozine-50 flow systems used for the Phase I and Phase II tests were modified and used to conduct the Phase IV tests. The sections of the systems downstream from the cut-off valves were changed by replacing the simulated Apollo propellant valves and injector assemblies with

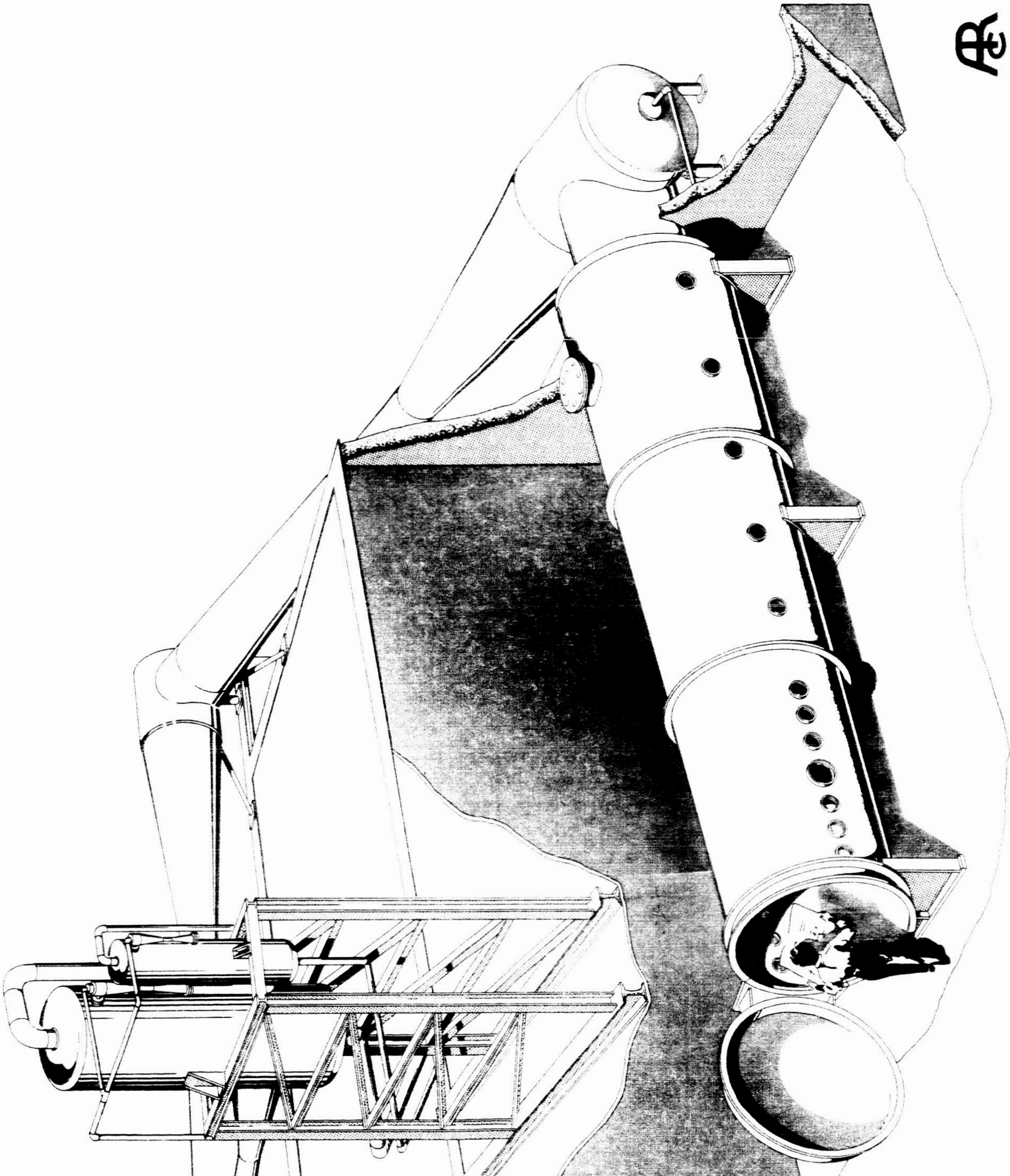

Figure 4-1. High Altitude Research Tunnel.

a Gemini RCS 25-pound thrust chamber assembly (GFE). None of the flow system components upstream from the cut-off valves were changed; however, some lines were moved slightly, relative to the tunnel, in order to allow the desired positioning of the Gemini TCA. The TCA assembly was mounted with the axis of symmetry of the combustion chamber horizontal in all tests. A schematic drawing of one of the two virtually identical flow systems is shown in Figure 4-2.

A purge line was installed between the Gemini TCA valve and the cut-off valve. The nitrogen gas purge system was used at the termination of a test as a means of clearing all residual propellant from the system, downstream from the cut-off valve.

Leakage was simulated by repeatedly pulsing the TCA valve by means of a specially designed electronic circuit. Both the cycle rate, 0.7 to 14 cycles per second, and the on-pulse duration, two to 15 milsec, could be varied independently to achieve various leak rates. The electronic circuit for this control unit is shown in Figure 4-6.

Simulation of the thermal environment of the Gemini Spacecraft, primarily the rate of heat transport (to or from the injector) for a given propellant temperature, is more difficult. The short time scheduled for completion of this program and initial unawareness of the existence of the 1.25-watt valve-heaters precluded a rigorous simulation of the thermal environment. Moreover, the contract work statement specified maintaining the propellant at temperatures of 20°F and 40°F and the injector at 20°F. Obviously, the latter is not realistic in the actual case if evaporative cooling occurs within the flow passages of the injector as expected.

The manner of simulation used in the testing was as follows. The propellant was maintained at the prescribed temperatures by means of a heat exchanger installed in the feed line upstream of the cut-off valve as shown in Figure 4-3. At the beginning of a test the injector was cooled to 20°F by a stream of cold carbon dioxide gas. During the tests the gas cooling was used only as required to keep the temperature of the

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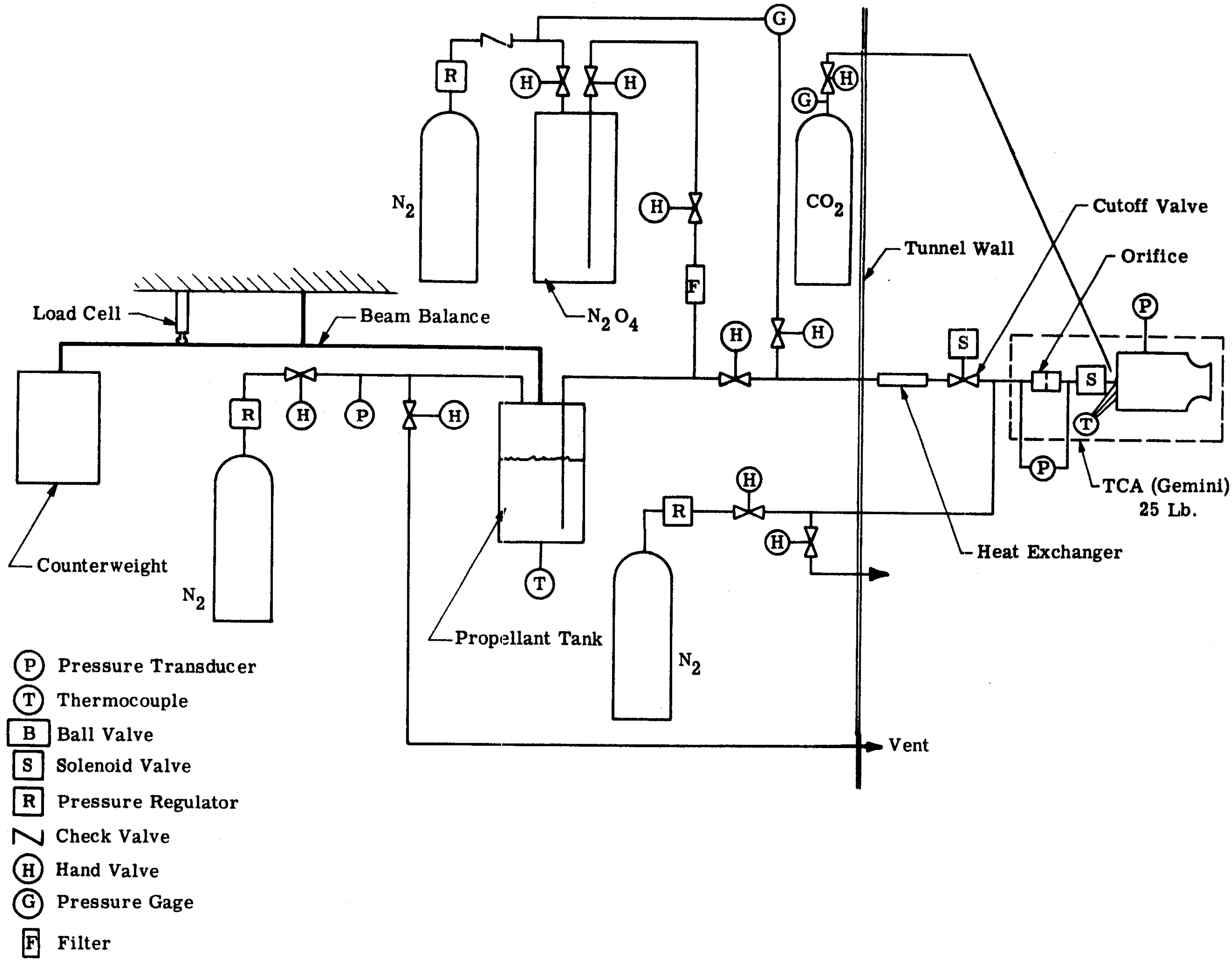

Figure 4-2. Schematic Diagram of Propellant Flow System for Phase IV Tests.

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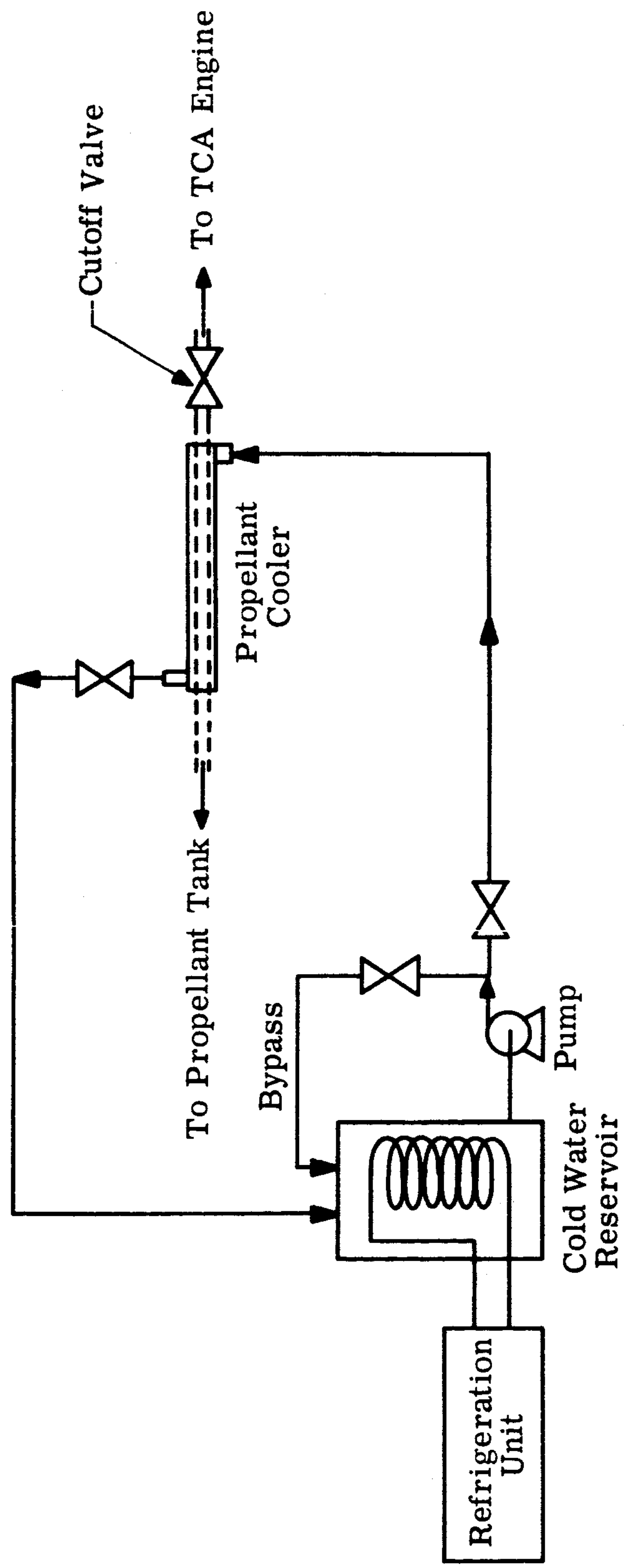


Figure 4-3. Coolant Flow Diagram.

injector from rising above 20°F. Under these circumstances, the injector is heated primarily by radiation from the walls of the vacuum chamber. Although not known precisely, the rate of radiative heat transport was probably of the order of 0.5 watt when the injector temperature was 20°F, and was not much different from the actual rate of heat transport supplied by the valve heaters.

It is concluded that any difference between the thermal environments of the experimental and the actual situation is small. Because of the much larger evaporative heat fluxes from nitrogen tetroxide, the difference was not critical to experiments with this propellant. With MMH, however, the difference may have been quite important because the evaporative heat flux at its triple point is very small.

The first 25 tests were conducted with the entire flow system located outside the high altitude tunnel. The Gemini TCA was exposed to the vacuum by inserting the nozzle through a hole in a specially designed aluminum port plate which was used to replace one of the glass ports in the tunnel. The Gemini TCA mounting flange, located about one inch from the nozzle unit, was cemented to the aluminum plate to form a vacuum seal. This installation method simplified plumbing of the flow system, instrumentation, and over-all operation of the test apparatus.

However, during test 25, frozen N_2O_4 accumulated in and apparently sealed the combustion chamber, causing a sharp increase in chamber pressure and resulting in a leak around the chamber pressure tap. Since this event created a potential safety hazard, the Gemini TCS was placed inside the tunnel. The TCA was mounted directly in front of one of the glass ports in the tunnel, with the nozzle exit facing this port. This allowed visual observation of the combustion chamber and injector face while the tests were in progress. Photographs, showing the installation of the Gemini TCA in the high altitude test chamber, are presented in Figures 4-4 and 4-5.

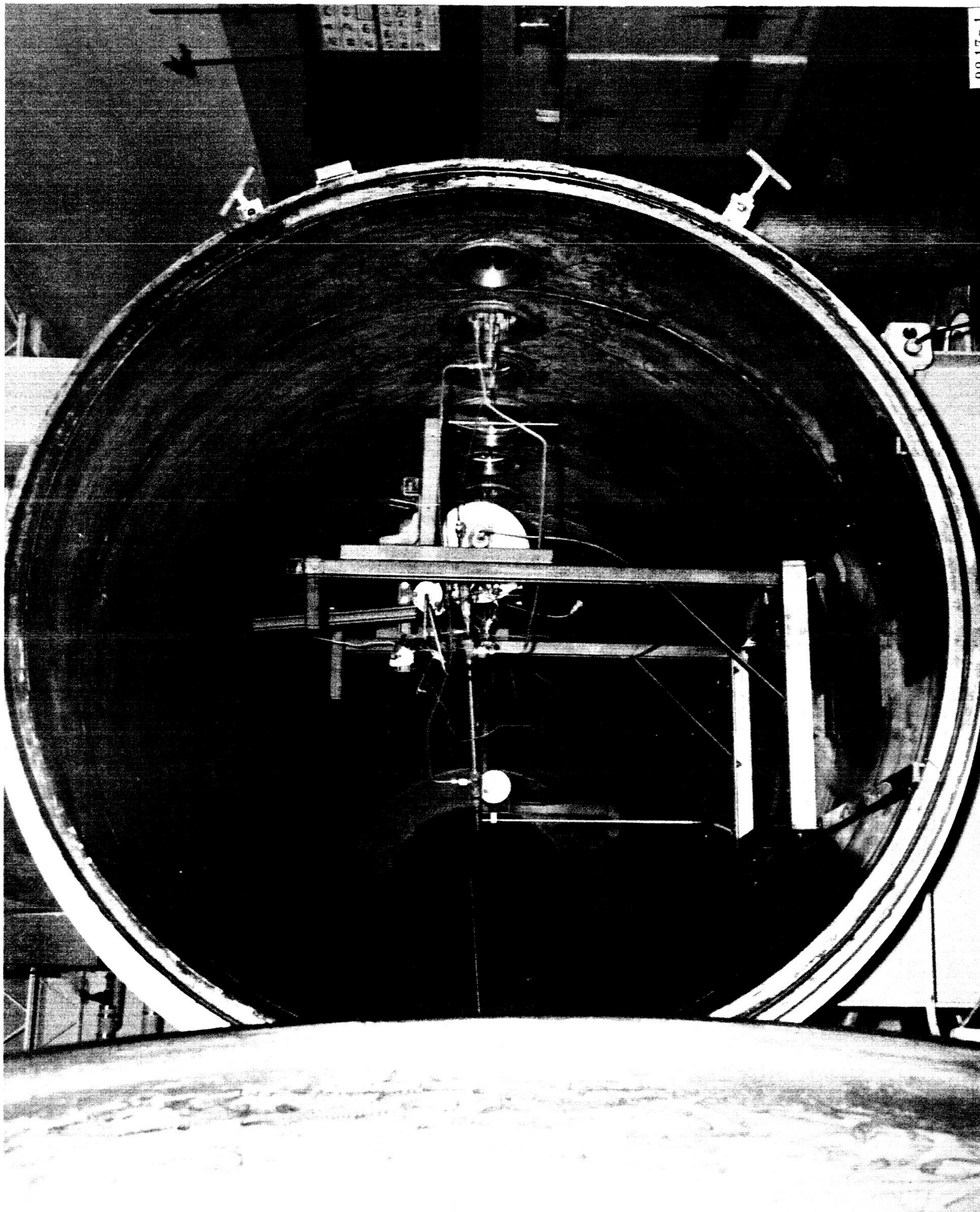


Figure 4-4. Photograph of Gemini RCS 25-Pound Engine Installed in High Altitude Tunnel.

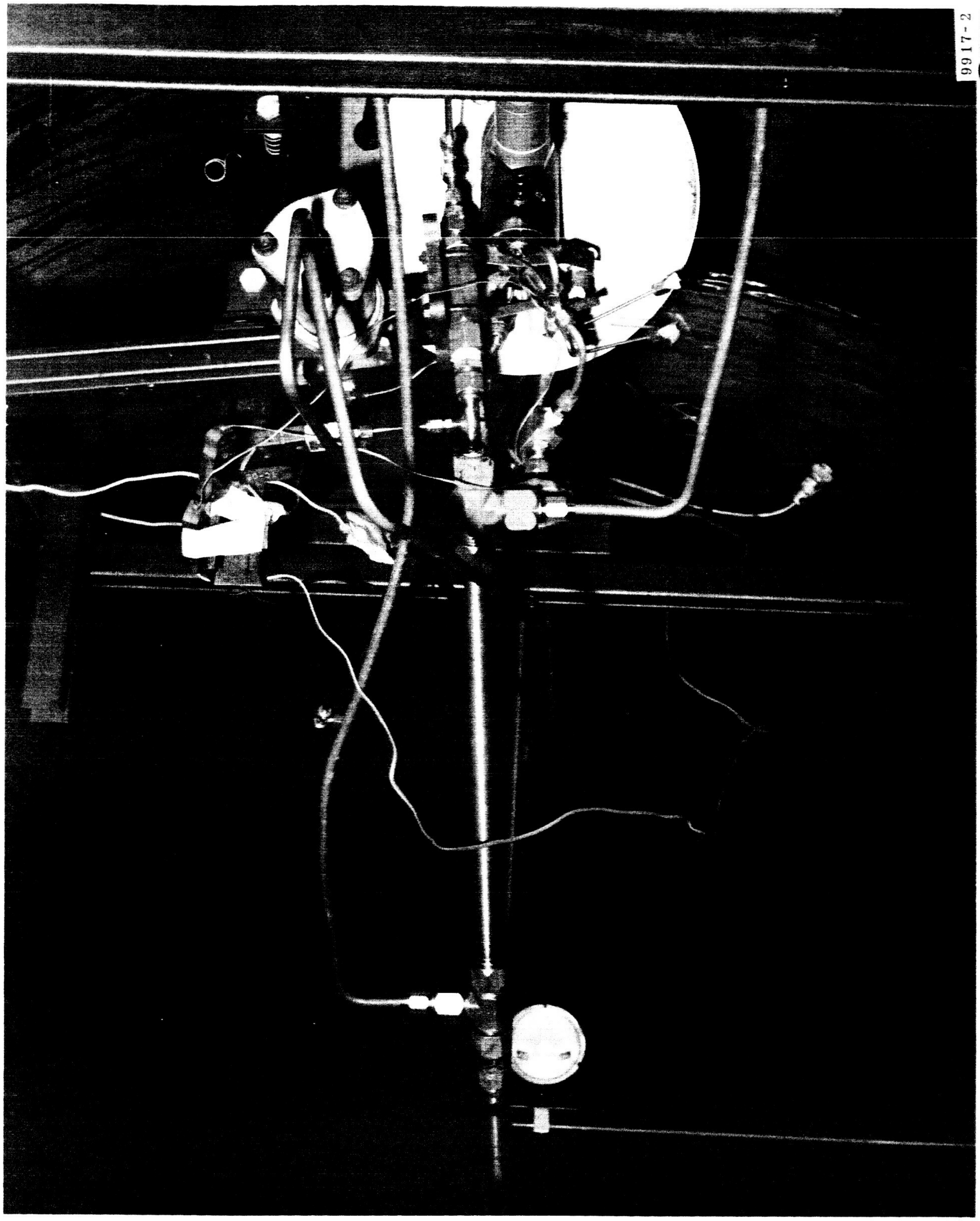
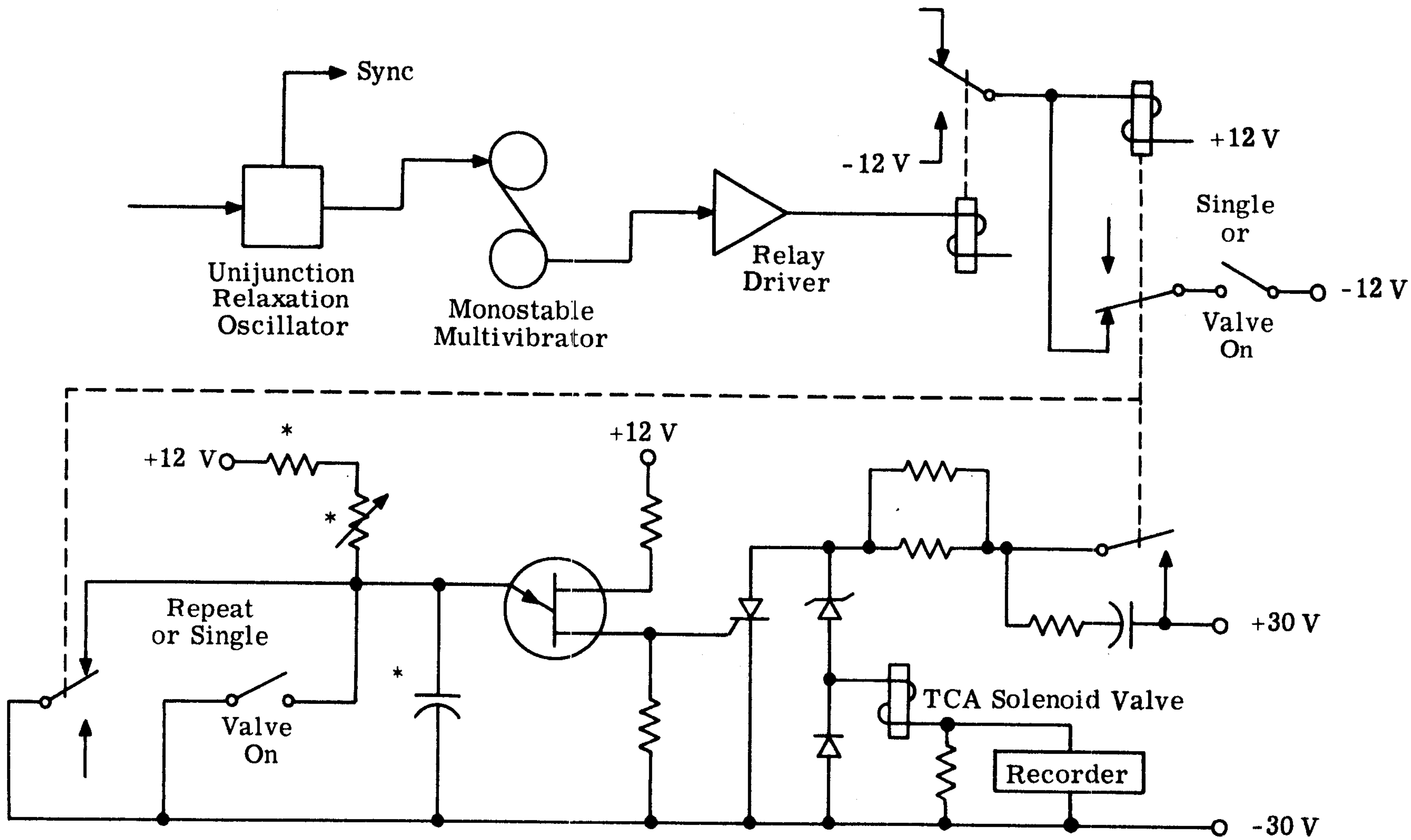


Figure 4-5. Photograph of Flow System used for Phase IV Tests.



*R and C Set for 1.6-8 msec

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Figure 4-6. Electronic Circuit for Pulse Mode Operation.

4.2.3 Instrumentation

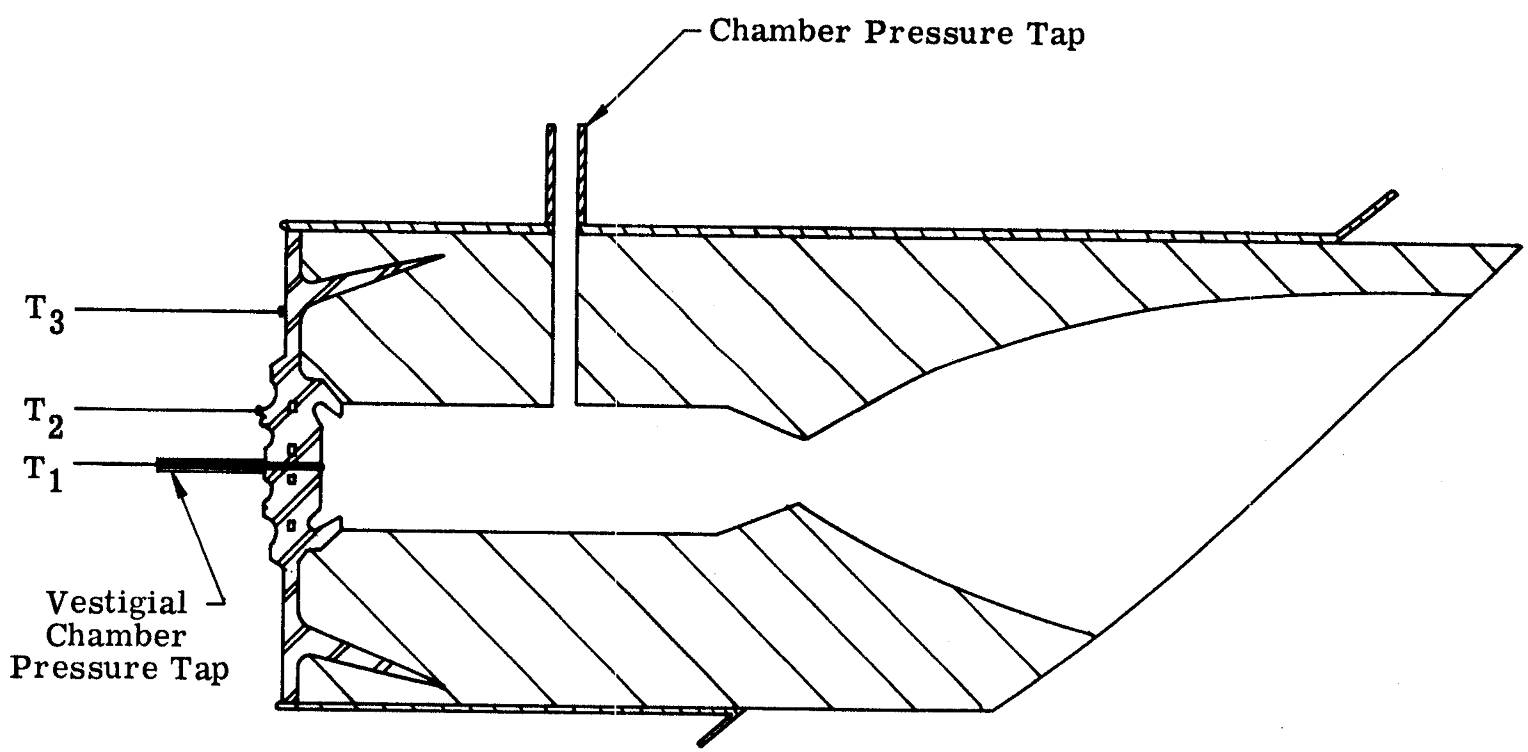
A multichannel recording oscillograph was used to simultaneously record the variables summarized in Table 4-1. Chart speeds from 0.1 to 80 inches per second can be obtained with this recorder.

Bare-wire thermocouples were used to measure temperature at locations shown in Figure 4-7. The T_1 thermocouple shown in this figure was inserted into an existing chamber-pressure probe tube attached to the center of the injector. The T_2 and T_3 thermocouples were soft-soldered to the back of the injector. Propellant temperature was measured by inserting a stainless-steel-sheathed thermocouple into the propellant line downstream from the heat exchanger. All thermocouple signals were conditioned by bridge circuits which allowed pre-run balancing and electrical calibration.

Propellant-tank and engine chamber pressures were measured by strain-gage-type pressure transducers. The power supplies that were used to provide the excitation voltage for the strain-gage bridge also contained electrical calibration circuits which provided pre-run calibration capabilities.

Propellant flow delays were determined by recording the current being applied to the propellant solenoid valve and measuring corresponding pressure-drop response across an orifice in the propellant line. These two variables were measured with a dual-beam oscilloscope as well as with the recording oscillograph. The magnetic-reluctance type differential pressure transducer that was used to measure the pressure-drop signal has a response of better than 3,000 cps. The sweep rate of the oscilloscope was set at 0.2 cm per milsec and the paper speed of the recording oscillograph was set at 20 inches per second. This allowed time resolutions to be made to within about one milsec.

Leak rates were measured by a special beam-balance system. It consisted of a beam suspended from a mounting plate by a thin sheet of stainless steel, which formed a sturdy, frictionless pivot. The propellant



Note: T_1 Thermocouple Inserted in Vestigial Chamber Pressure Tap. Bead Located at Inner Surface of Injector.

Figure 4-7. Location of Injector Thermocouples and Chamber Pressure Tap on 25-Pound Thrust RCS Test Engine.

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TABLE 4-1

VARIABLES RECORDED BY OSCILLOGRAPH

Variable	Sensors	Location of Sensor
Tank pressure	Strain-gauge pressure transducer, 0-250 psig	Tank pressurizing line
Rocket chamber pressure	Strain-gauge pressure transducer, 0-250 psig	Rocket chamber
* Pressure drop across propellant-line orifice	Differential pressure transducer, 0-250 psig	Across orifice in propellant feed line
Injector temperature (T_1)	Chromel-Alumel thermocouple	Center of injector plate (Fig. 4-7)
Injector temperature (T_2)	Chromel-Alumel thermocouple	1/3 of the distance from center to edge of injector (Fig. 4-7)
Injector temperature (T_3)	Chromel-Alumel thermocouple	2/3 of the distance from center to edge of injector (Fig. 4-7)
Propellant temperature (T_p)	Iron-constantan thermocouple	Inside the propellant feed line, downstream from heat exchanger
* Valve current	Voltage drop across 1.5 ohm resistor	In series with propellant-valve solenoid coil
Leak Rate	Force transducer (Reluctance type)	Beam balance
Tunnel Pressure	Ionization type vacuum gage	Tunnel wall 12 inches from door

* These variables were also monitored by a dual-beam oscilloscope.

tank was attached to one end of the beam and a suitable counterweight was attached to the other end. A force transducer mounted between the beam and a stationary mounting plate signaled changes in weight of the tank contents versus time to the recording oscillograph.

For the first 24 tests the test apparatus was mounted outside the tunnel in the manner described above in Section 4.2.2, and the remainder of the tests were conducted with the rocket engine mounted entirely inside the test chamber. During these latter tests, 16 mm motion pictures were taken of the leaking phenomena that occurred in the engine combustion chamber. The photographic and lighting technique that was used is illustrated in Figure 4-8.

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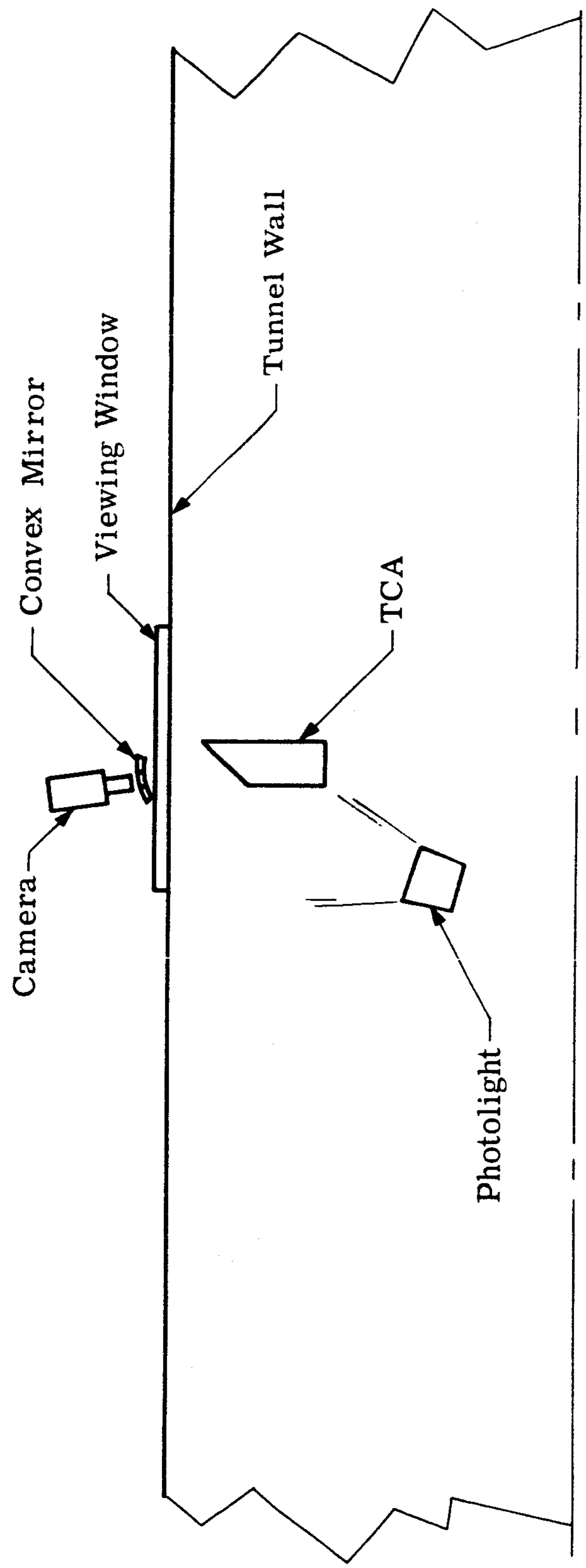


Figure 4-8. Photographic Technique.

4.3 TEST PROCEDURE

Three types of tests were performed:

1) Calibration tests to determine the times required, after opening the TCA valve, for flow initiation and full flow to be achieved when no propellant freezing occurred;
2) Dribble-Volume Freezing Tests to simulate engine shut-down and reignition; and
3) Leak tests

Prior to performing the tests, the propellant tank mounted on the balance beam (See Figure 4-2) was filled by closing the hand cut-off valve, drawing a partial vacuum on the tank, and opening the fill valve. After the propellant tank was filled, the hand valve was closed. The line between the hand valve and remotely controlled cut-off valve was then evacuated to tunnel pressure (approximately 20 μHg) and filled with propellant by pressurizing the tank with GN_2 to 300 psig, closing the remotely controlled valve, and opening the hand valve.

Shortly before initiating a test the TCA and the propellant line downstream from the remote cut-off valve were purged thoroughly with GN_2 to remove residual liquids. The purge valve was closed and all flow or void spaces located between the cut-off and TCA valves were evacuated to tunnel pressure through a vent in the purge line. These volumes then were filled with propellant by closing the TCA and vent valves and opening the remotely controlled cut-off valve. At this point, the flow system was ready for either of the three classes of tests mentioned above.

The final pre-test operation was injector cooling. Expanded CO_2 was sprayed on the back of the injector until T_1 (see Figures 4-2 and 4-7) was 20°F. Then the CO_2 flow was stopped, and the test was begun.

The discussion thus far has pertained to procedures which were performed in preparing for all tests. The following sections discuss the continued special procedure according to the type of test being conducted.

4.3.1 Calibration Tests

These tests were conducted by opening the TCA propellant valve for a period of time sufficient to assure that full flow had been obtained (approximately three seconds). During the opening and closing, the oscillograph chart speed was 20 ips, so that a one milsec time resolution was possible. In addition, an oscillo-photograph was made of the valve current and differential-pressure transducer responses.

Two base-line delay times were obtained from these tests:

1) Flow-Initiation Delay, defined as the time elapsed between the first movement of the valve-current trace and the first movement of the differential-pressure trace, and
2) Full-Flow Delay, defined as the time elapsed between the first movement of the valve-current trace and first indication of full flow on the differential-pressure trace.

Several of these tests were made on each propellant valve to examine the reproducibility of the valve operations. The base-line flow-initiation delay and full-flow delay were 5.5 and 9 milsec, respectively, for both valves.

4.3.2 Dribble Volume Freezing Tests

The on-time control of the valve-pulsing device (see Section 4.2.2 and Figure 4-6) was adjusted such that the valve trace, displayed on the oscilloscope, indicated current flow for a preselected period of time (6 to 11 milsec) with the purge GN_2 flowing through the valve. Then the propellant line was filled with propellant up to the TCA valve, as discussed above.

The test was conducted by allowing the valve to pulse once, waiting for a specific period of elapsed time (2 sec to 13 min), and then opening the valve until full flow was attained. The oscillograph chart was operated at a slow speed during tests involving waiting periods in excess of about one minute; however, the speed was increased to 20 ips just prior to opening of the valve at the end of the test.

4.3.3 Leak Tests

The on-time and frequency controls of the pulsing device were adjusted initially to their minimum settings. With the device operating, the valve would not open under these conditions.

After the propellant line had been filled up to the TCA valve, and the tank pressure had been adjusted to the desired level, the valve cycling was initiated. The valve on-time was increased until the desired initial (nominal) flow rate was achieved.

Leakage was allowed to proceed until the occurrence of one or more of the following:

1) A long period of time had elapsed during which the flow-rate was constant and none of the recorded temperatures exhibited significant changes;
2) the flow rate decreased greatly or stopped altogether;
3) the injector temperatures, particularly T_1, dropped to a very low level; or
4) considerable frozen propellant had accumulated in the combustion chamber.

When one or a combination of these phenomena occurred, the TCA valve was opened until full flow was evident.

The oscillograph chart was operated at one ips during the leak period and was increased to 20 ips just prior to opening of the valve at the end of the test. After the valve was closed, the speed was reduced to one ips, and the injector temperatures were recorded for a short time beyond shut-down.

Delay times associated with flow after the full opening of the valve at the termination of the leak test were determined by the technique discussed in Section 4.3.1. The corresponding base-line values were subtracted from these delay times to obtain the flow initiation and full flow delays caused by propellant freezing.

The earlier leak tests were conducted with 300 psig tank pressure during the entire run. Because of the cyclic operation of the valve during the leak period, an intermittant spray of propellant emitted from the injector ports during some tests. In an attempt to reduce the velocity of the propellant through the flow passages during the valve pulses, some of the later runs were made with a tank pressure of about 5 psig. In these cases the valve cycling was stopped, and the tank pressure was increased to 300 psig just prior to full opening of the valve. Runs I-26, I-27, I-28, I-29, I-31, I-32 and I-45 were conducted in this latter manner.

4.4 DATA AND RESULTS

4.4.1 Dribble-Volume Tests

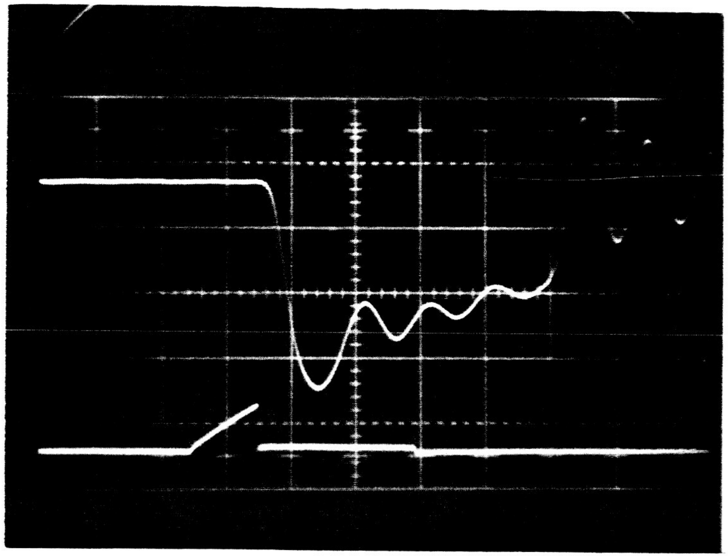
"Dribble Volume" is defined as the residual propellant remaining between the propellant valve and injector after engine shutdown. A total set of 11 dribble volume tests (10 with N_2O_4 and one with MMH) was performed to investigate the possibility of evaporative freezing of the dribble volume upon exposure to a vacuum environment. The procedure for these tests consisted of energizing the propellant valve solenoid for periods of approximately 6, 8 and 10 milsec to fill the flow passages and then waiting for periods of 2 seconds to 13 minutes before opening the valve to establish flow. No flow delays were observed in the dribble volume tests with N_2O_4 or MMH, which indicated that if any freezing of propellant did occur, it was insignificant. Also, an examination of the injector temperature data showed no indication of freezing. The detailed procedure used for conducting these tests is described in Section 4.3.2.

4.4.2 Leak Tests

Propellant leaks through the Gemini poppet-type propellant valves were achieved by pulsing the valves in a cyclic manner, as described in Section 4.3.3. This type of leak was obviously not as severe a test as a steady, trickel-type leak through a faulty seal would have been. Each time the valve was pulsed, a slug of propellant of sufficient quantity and momentum was passed through the valve to disturb any freezing of the previous slug of propellant which may have occurred in the injector manifold system. The pulsing technique for obtaining a leak simulation was chosen because the welded construction used on the Gemini flow system, and the very limited time available for completing the work, precluded the use of any other leaking technique. (e.g., scoring the valve seat, constructing a substitute valve-mockup, etc.)

A total set of 25 leak tests was conducted: 22 with N_2O_4 and three with MMH. Primary emphasis was placed on N_2O_4 rather than MMH because no freezing was observed or expected during the MMH tests (see discussion of Section 3.0). The data recorded by a recording oscillograph have been reduced and plotted for the tests during which no experimental difficulties were encountered. These data are presented in Appendix A of this report. In addition to the recording oscillograph, an oscilloscope was used to monitor valve pulses and propellant flow delays. Flow delays were determined by using a differential-pressure transducer across a flow-control orifice, as described in Section 4.2.3. A Polaroid camera, attached to the oscilloscope, provided a permanent record of the valve-pulse duration and the corresponding flow signal from the differential-pressure transducer. Figure 4-9 shows two typical photographs of pulses obtained during the N_2O_4 leak tests. Sweep speed of the scope was set at 0.2 cm per milsec, which allowed an accurate resolution of time to one milsec. The oscilloscope measures the voltage drop across a fixed 1.5Ω resistor connected in series with the valve solenoid; therefore, the vertical scale is directly proportional to the valve current. This circuit is shown in Figure 4-6. Figure 4-9(a) shows that the valve was energized for five milsec, and Figure 4-9(b) shows a pulse duration of eight milsec. In both cases the differential-pressure transducer responded 5.5 milsec after the valve was energized, and flow was indicated for periods of approximately 23 and 29 milsec, respectively. This suggests that the valve apparently did not completely close immediately after the valve was deenergized, but, rather, allowed some propellant flow for a short period of time after the electrical pulse was terminated.

The low-level current plateau that immediately followed the pulse termination command in Figure 4-9 shows that a small residual current, approximately 0.03 amp, remains in the valve circuit for a short period of time. The extent to which this residual current contributed to the sluggish valve-closing operation is unknown. However, the current dropped to zero at least 10 milsec before the pressure transducer indicated that the valve was closed. If the low-level (plateau) current was, indeed, holding the valve open, it would be expected that the flow-meter indication of valve closure would have occurred within about 1 or 2 milsec. In any event, since the procedure for the calculation of leak rates produces average values over time intervals that involved many valve pulses, the exact opening



a

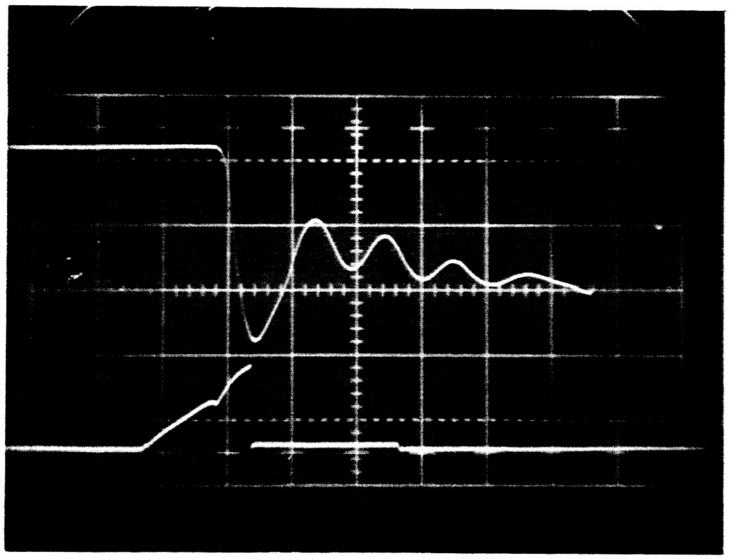


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Figure 4-9. Oscilloscope Display of Solenoid Valve Pulse and Propellant Flow Measurement.

and closing characteristics of the valve do not affect the results.

Evaporative freezing of N_2O_4 was experienced even though the leaks obtained by the pulse-mode operation did not provide as severe a test as would have been obtained using a steady, trickle-type leak. Data indicate that freezing occurred in the cavity between the propellant valve and the injector, and visual observations identified extensive freezing in the combustion chamber. For the higher leak rates the combustion chamber appeared to be filled with frozen N_2O_4. In several tests frozen N_2O_4 was extruded through the nozzle throat, and in two cases chamber pressure increased to 294 and 253 psia for about 40 milliseconds shortly after the valve was opened indicative of a blockage in the nozzle vicinity.

The most important measurement made was the determination of the extent of flow delay caused by evaporative freezing and plugging. Unfortunately, the flow passages of the manifold and injector temperature at a location within 1/8 inch from the flow passages. The determination of flow delay was made by the measurement of the pressure drop across the flow control orifice. Two types of flow delays were determined, as defined in Section 4.3: <u>flow-initiation delay</u> and <u>full-flow delay</u>. Flow delays for all the valid N_2O_4 leak tests are listed in Table 4-2. An average leak rate during the run is also tabulated in Table 4-2. Leak rates fluctuated during a test (see Appendix A) over a fairly wide range and therefore it is difficult to associate flow delays with a single, specific leak rate. The average leak rates reported in Table 4-2 were obtained by measuring the propellant weight change in the propellant tank during the entire leak period and dividing by the total leak time. Attempts were made to correlate flow delay and leak rate by using numerous techniques for choosing a representative leak rate, but no meaningful correlation could be obtained with the available data. Additional details of the analytical procedure, together with the interpretation and significance of the results, are presented in Section 4.5.

TABLE 4-2

SUMMARY OF FLOW DELAYS DUE TO VALVE LEAKAGE

Ave. Leak Rate (cc/sec)	Run No.	t_1 (msec)	t_2 (msec)
0.0012	44	2	2
0.0018	42	2	2
0.0029	45	4	4
0.0066	18	16	76
0.0076	46C	1	150
0.010	31	2	71
0.011	32	0	0
0.012	29	0	91
0.017	36	1	27
0.018	28	0	116
0.026	46B	0	115
0.022	39	1	156
0.023	27	0	0
0.023	40	0	0
0.036	38	1	112
0.037	26	0	0
0.065	46A	1	552

t_1 - **Flow-initiation delay (see Section 4.3)**

t_2 - **Full-Flow delay (see Section 4.3)**

Flow delays of some extent were measured during most of the N_2O_4 leak tests, but no flow delays or indications of freezing were apparent during the MMH tests. For the N_2O_4 tests, the most significant flow-initiation delay observed was 21 milsec which is 16 milsec longer than the base-line delay discussed in Section 4.3.1. In the same test, the full-flow delay was 85 milsec or 76 milsec longer than the base-line calibration. The longest full-flow delay observed was 552 milsec.

For most tests in which flow delays of either type were observed, temperature data for the injector indicated freezing within the flow passages. When the propellant valve was opened at the end of a leak period, the injector temperature usually increased because of the influence of the warmer propellant flowing through the injector. During the N_2O_4 tests, when the propellant valve was closed, the injector temperature usually dropped well below 0°F, and in one case dropped to -36°F. This was attributed to sublimation of frozen N_2O_4 which collected on the injector face and splash plate while the valve was open.

During the MMH tests no freezing was observed in the combustion chamber when the valve was opened at the end of a test. Consequently, when the valve was closed very little change in injector temperature was noted.

4.5 ANALYSIS

The experimental observations just described may be readily interpreted within the theoretical framework outlined in Section 3.0 of this report and in the report for Phase I (Reference 3). Indeed, there is substantial agreement between experiment and theory. That freezing of nitrogen tetroxide, but not MMH, can occur within their respective propellant manifolds, as indicated by the observation of flow delays and the measurements of injector temperature, is a result predicted by the theory. Moreover, the observed lack of flow delays and injector cooling in the "dribble volume" experiments is explained by the consideration that the sensible heat of the injector and manifold is very much greater than the total heat necessary to completely vaporize the residual propellant. On the other hand, the theoretically predicted range of leak rates in which flow stoppages and freezing in the manifold must occur, could not be determined from the experiments performed. Through consideration of the flow and evaporative processes, it may be shown that this results from the artificial characteristics of the method used to simulate the leak. This is discussed in detail in the following paragraphs. A seeming discrepancy, that leaked MMH did not freeze in the combustion chamber as predicted, is discussed subsequently.

The theoretical development described in Reference 1 was based on the assumed condition of a steady rate of leakage (which also would most closely represent an actual leakage situation). This theory was then applied (Section 3.0 of this report) to calculate the maximum and minimum rates of leakage for which propellant can freeze within the manifold. Experimentally, the steady leakage condition was not fulfilled, but instead the "leak" was a rapidly pulsating, on-off flow. During each pulse the propellant flow-rate approached the rated full-flow which is much greater than the maximum leak rate for freezing in the manifold. Moreover, the flow during a single pulse was sufficient to fill completely or at least a significant fraction of the manifold volume. Thus, frozen propellant formed from the liquid left by one pulse tends to be washed away by the next.

In effect, the experimental technique to produce leakage was a series of "dribble volumes". According to the observations already described, a single residual volume of propellant cannot freeze. However, freezing is conceivable for a series, since the metal parts of the injector are continually cooled by the evaporation and boiling which each succeeding quantity of residual propellant undergoes. In this way, the nearby parts of the injector may become sufficiently cold to permit the freezing of propellant.

On the other hand, freezing in the manifold cannot be expected for any given series of pulses; the occurrence of such freezing must be random. The reason for this has been observed many times during the pulsating flow of a liquid through a small opening into a vacuum. The momentum imparted in each pulse causes some of the liquid to squirt through the injector ports. After the motion subsides, the liquid which remains in the ports evaporatively freezes immediately. In this way, the ports are plugged between pulses, and the propellant inside the manifold cannot evaporatively cool and freeze. Although the plugs are sufficiently strong to withstand a small vapor pressure, they are blown free by the high pressure accompanying the next pulse of liquid, and the whole process then repeats itself. Nevertheless, it is possible during a series of a few pulses that one or more of the ports will not be plugged because of some momentary variation in the prevailing pulsatile flow pattern, and freezing may then occur within the portions of the manifold associated with the injector ports involved.

To sum up the discussion thus far, the character of the leakage mode used in the experiments was vastly different from the usual, trickle type of leak which was assumed for the theoretical analysis in Section 3.0. Instead, the flow consisted of a succession of pulses for which freezing within the manifold generally cannot occur because the injector ports usually are plugged with frozen propellant between pulses. However, random flow variations may leave some parts free during a series of a few pulses and permit freezing in the manifold.

As described in Section 3.0, the nitrogen tetroxide manifold consists of a set of radial ducts, each terminating in a single port. Thus, for the pulsatile flow used for leakage simulation, freezing when it occurs is most likely to occur only in one or two of the ducts at a time. Accordingly, this explains why only full-flow delays were observed usually, and significant flow-initiation delays were observed only rarely. More important and for the same reason, the pulsatile flow method cannot produce as severe a freezing condition as would result from the normal, trickle-type leak. This is because the latter could lead to freezing near the valve seat or in the feed duct to the manifold. In this event a flow-initiation delay would be likely.

Nevertheless, the experimental results do demonstrate that leaking nitrogen tetroxide can freeze in the manifold of a Gemini 25-pound TCA and that such freezing can cause significant full-flow delays.

Another result of the pulsatile flow is that no correlation between average "leak" rate and the occurrence of freezing can be expected, because of the random nature of its occurrence. Thus maximum and minimum leak rates for freezing could not be observed experimentally. Instead reliance must be placed on the values calculated theoretically and presented in Section 3.0. These values are believed to be quite accurate. The validity of the theory upon which they are based has been demonstrated in the leakage experiments conducted in Phase I of this program. For illustration, Figure 4-10 shows the theoretical maximum and minimum leak rates of nitrogen tetroxide, at selected initial temperatures, computed for one of the experimental valve-manifold-injector systems used. Also plotted are observed leak-rate values for which either significant flow-initiation delays, absence of delay but freezing in the manifold, or absence both of delay and freezing occurred. In general there is good agreement between the experimental results and the theoretical predictions.

Turning now to the freezing of MMH, no freezing of this propellant within the combustion chamber was observed, although this was predicted theoretically for very low leak rates. The probable reason for this is that the MMH used in the experiments contained a small amount of water, which according to specifications must have been less than 2 per cent by weight. Upon exposure to vacuum, evaporation produces a further increase in water concentration since the vapor is nearly pure MMH. Thus the final mixture may freeze at a pressure significantly less than 0.1 torr, the triple-point pressure of the pure material. In this event, the vacuum attainable in the High Altitude Facility is not sufficiently low to evaporatively freeze this material. Moreover, the maximum leak rate for freezing in the combustion chamber, computed in Section 3.0 also should be much less.

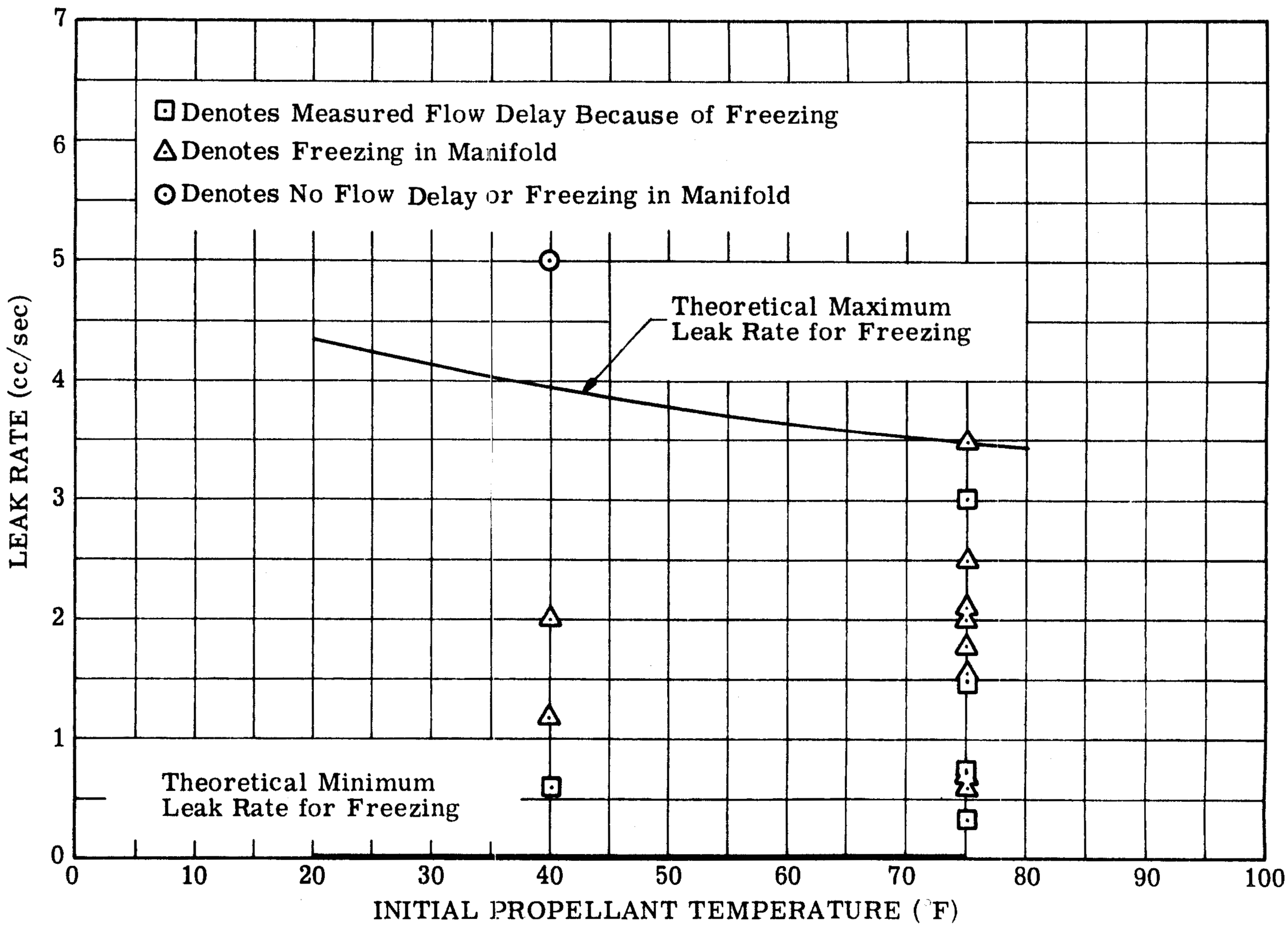

Figure 4-10. Comparison of Theoretically Calculated and Experimentally Measured Leak Rates Resulting in the Accumulation of Frozen Nitrogen Tetroxide Within the Manifold of an Injector Having a Total Port Area of 0.0463 in^2.

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5.0 CONCLUSIONS AND RECOMMENDATIONS

The principle result of this investigation was the experimental and theoretical demonstration that leaking nitrogen tetroxide can freeze evaporatively in the injector manifold of 25-pound and 100-pound TCA engines, and obstruct subsequent flow. Furthermore, as was noted in the experimental work for Phase I, the obstructions grow and break in a cyclical manner, with the result that the seriousness of the blockage depends on the moment in the cycle at which the propellant valve is opened.

Ignoring, for the moment, the possibility of explosive pressure transients upon ignition, this result is not particularly serious from the point of view of NASA's Gemini program. The intermittent character of the blockages means that an OAMS engine with a leaky oxidizer valve will not produce full thurst in the <u>pulse mode</u> on some occasions and will deliver full thrust in the <u>direct mode</u> only after some delay. The eventual successful operation of the engine in the direct mode is expected because the resistive heating of the energized solenoid valve and the static pressure of the propellant eventually will clear the frozen material. The consequence of these occurrences alone, is some loss of the precision with which the spacecraft can be maneuvered. On the other hand, compensation for this can be made by proper use of those remaining OAMS engines which are unafflicted.

For the RCS engines, the freezing of leaking oxidizer is even less a problem because of the redundancy of engines and the fact that the propellant feed system remains dry until just prior to use.

However, these considerations may be academic because of the possibility of a "hard start" and the occurrence of explosive pressure transients within the combustion chamber when restart of an engine with a blocked oxidizer manifold is attempted. Even under normal circumstances the restart, in a vacuum, of a rocket engine with nitrogen tetroxide and MMH will be accompanied by a "pressure spike" of some magnitude. The magnitude of this "pressure spike" is believed to depend upon the amount of well-mixed fuel and oxidizer which accumulates within the combustion chamber prior to ignition. Such accumulations may stem from evaporative cooling and freezing of propellants upon entering the combustion chamber, and a resultant delay of hypergolic ignition. When ignition finally occurs, the mixture may detonate or burn explosively.

Momentary blockage of the nitrogen tetroxide manifold with frozen propellant, and the resulting uncontrolled fuel-lead, only aggravates this problem. In this case, while the flow of nitrogen tetroxide is blocked, MMH flows freely into the combustion chamber and accumulates. Also, although it will not freeze (the rate of full-flow is much greater than the maximum leak rate for freezing), the MMH will cool evaporatively to a very low temperature, probably less than 0°F. Finally, after the blockage in the nitrogen tetroxide manifold breaks free, oxidizer flows into the chamber and delayed hypergolic ignition occurs, as in the case described above. However, in addition to the explosive combustion of the mixed fuel and oxidizer, the excess fuel accumulated prior to oxidizer flow undergoes a well-known exothermic and explosive decomposition which of course would increase the severity of the "pressure spike". Moreover, it is possible that the cold fuel accumulated prior to the start of oxidizer flow may delay further the hypergolic ignition and contribute still more to the "pressure spike".

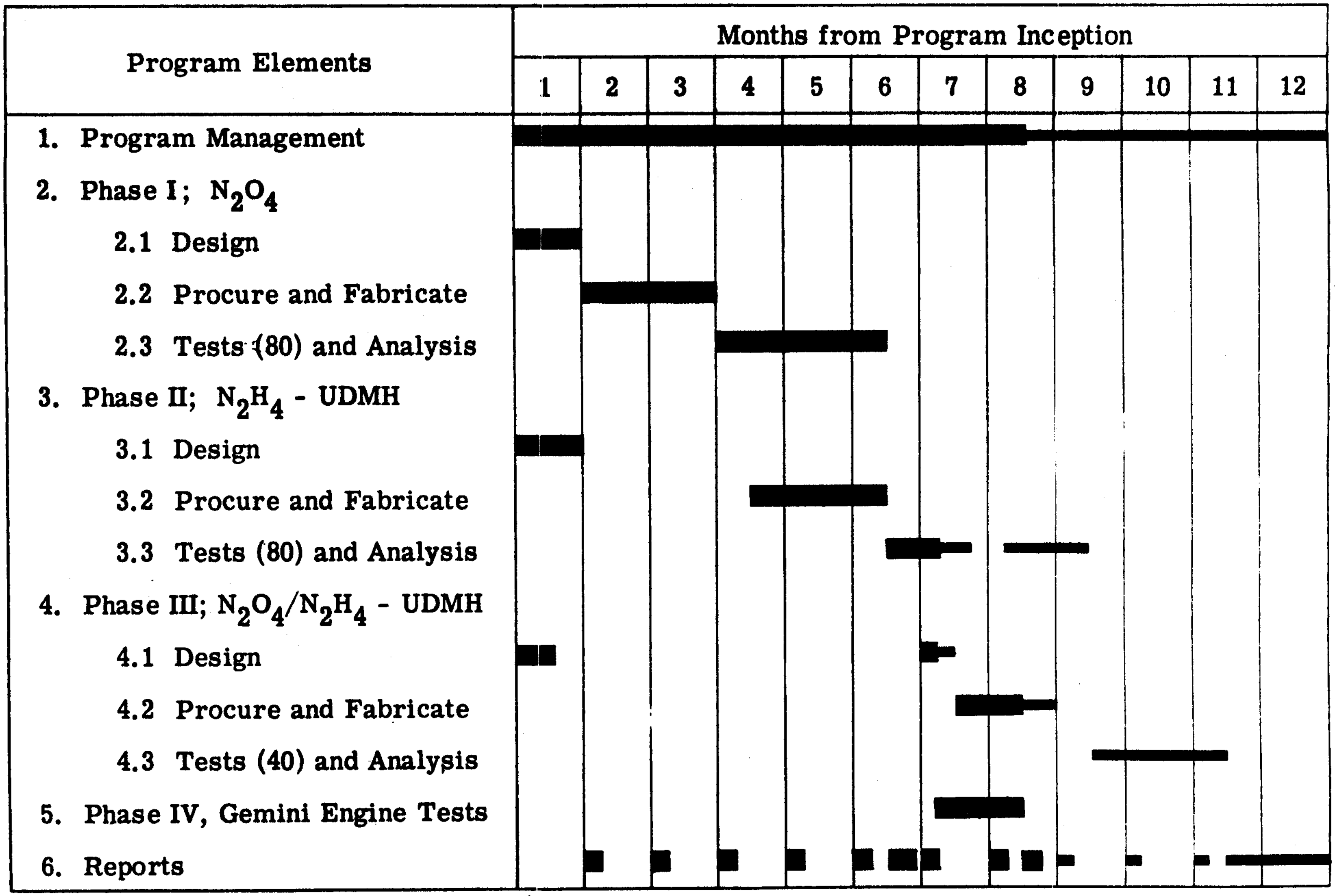
Obviously, such "hard starts" pose a threat to the entire Gemini spacecraft. On the other hand, no data are available to substantiate the likelihood that such "hard starts" will indeed result from uncontrolled delays in the flow of oxidizer. This is the objective of Phase III (of the overall valve-leakage program) which is to be undertaken in the very near future.

In view of this, the seriousness of oxidizer valve leakage and freezing of nitrogen tetroxide within the propellant manifold cannot be accurately assessed for the Gemini spacecraft at this time. Consequently, it is also premature to recommend a study to develop remedial devices and techniques for use with the OAMS engines. No acceptable "quick fixes" are available for the freezing problem; instead, the development of a remedy will involve considerable study and testing, especially acceptance testing to assure that the remedy unwittingly does not introduce other problems.

6.0 PROGRAM STATUS

The program schedule, showing accomplishments to date and work remaining, is presented in Figure 6.1. Work in Phase II has slipped by approximately one week, due to the Gemini (Phase IV) tests; however, the overall program will be brought back on schedule in a few weeks by operating on a two-shift basis.

Approximately 7,610 man hours were expended to complete the work shown in Figure 6.1. This expenditure represents about 67 per cent of the effort for the total program.



Denotes Degree of Element Completion

Figure 6-1. Program Schedule.

LITERATURE CITATIONS

1. Atlantic Research Corporation, "Investigation of the Effects of Vacuum on Liquid Hydrogen and Other Cryogens Used on Launch Vehicles," Final Summary Report by J. A. Simmons, R. D. Gift and M. Markels, Jr. for Contract NAS8-11044, December 18, 1964.

2. Atlantic Research Corporation, "Study of Propellant Valve Leakage in a Vacuum," Technical Proposal ARC No. 43-2579, February 24, 1965.

3. Atlantic Research Corporation, "Study of Propellant Leakage in a Vacuum," Phase I Report, 7 June 1965 to 24 November 1965, Contract No. NAS 9-4494.

APPENDIX A
LEAK TEST DATA

This appendix contains the data obtained during the 17 Phase I (N_2O_4) and three Phase II (MMH) successful leak tests. Injector temperatures, propellant temperature, and flow rate are plotted versus time for each run, and all other data and operating conditions are presented in notes appearing on the graphs.

Time zero on these plots is defined as the instant that voltage is applied to the valve during the valve-opening operation at the end of the leak period. Thus, negative time applies to the leak period, and positive time applies to the valve opening and closing operation at the end of the test.

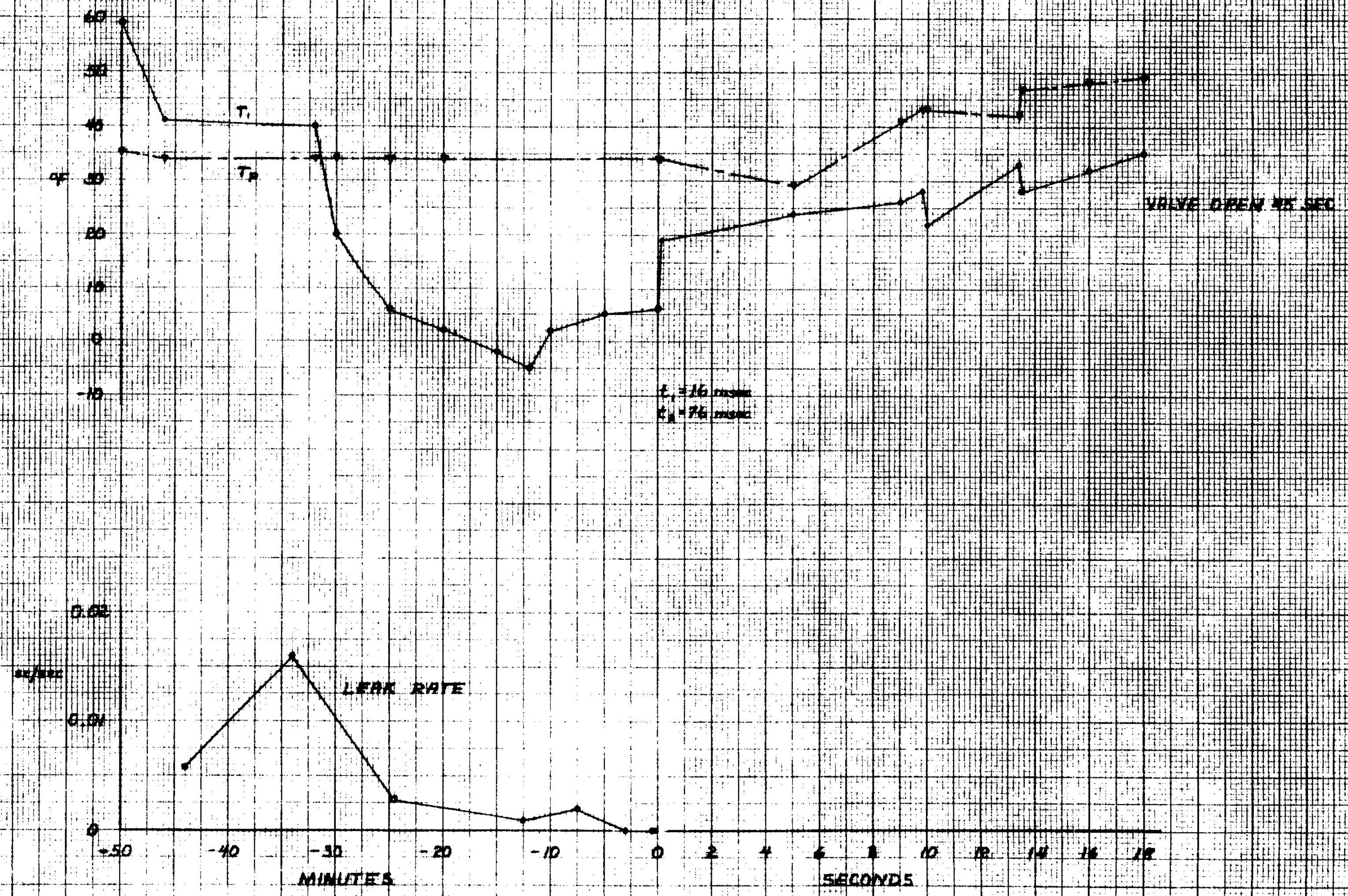
All of the temperatures are plotted on the same temperature scale for a given run and are labeled according to the nomenclature defined by Table 4-1 and Figure 4-7.

The delay times noted on the curves are the times measured in excess of the non-freezing (or baseline) case. They are abbreviated as:

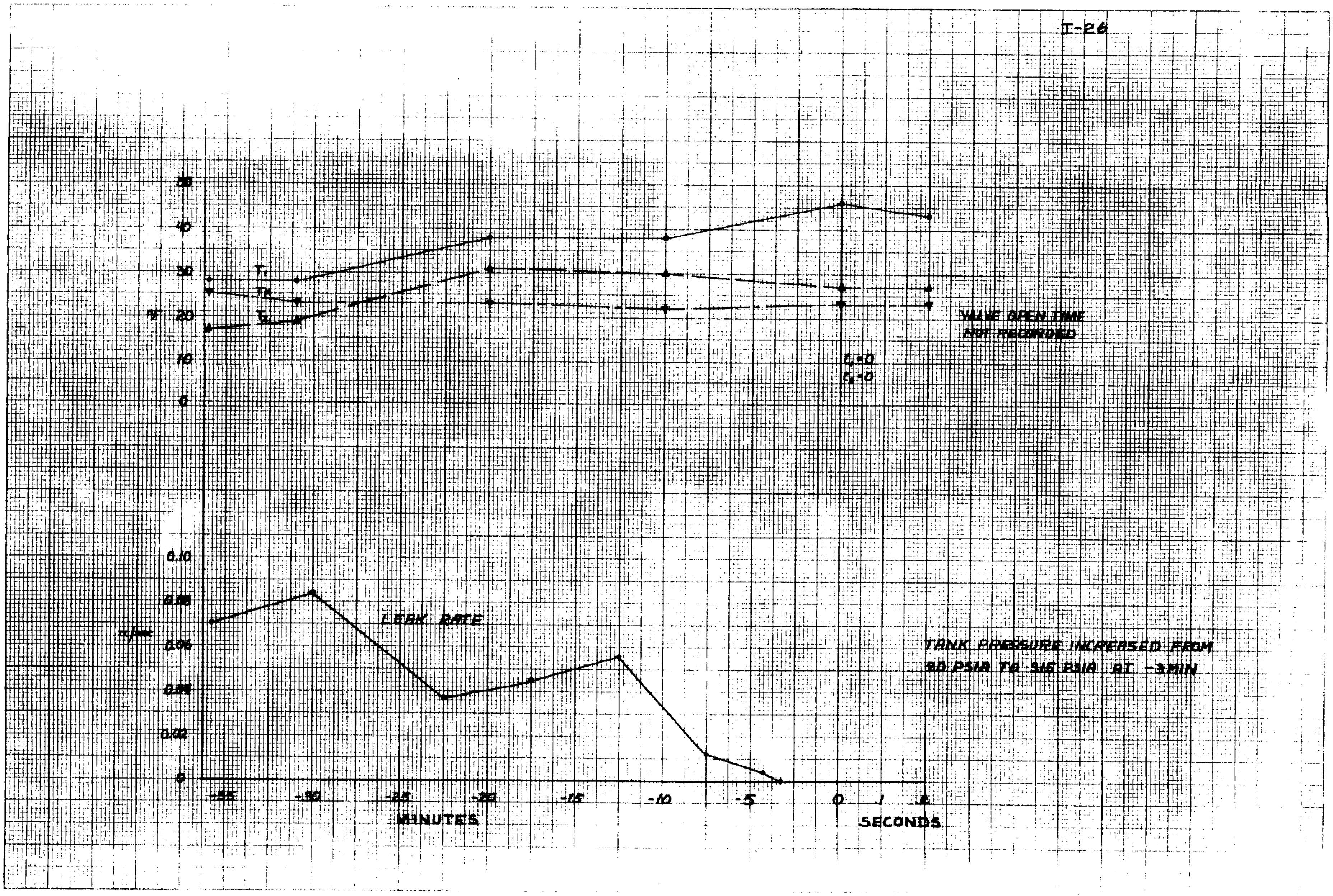
t_1 = <u>flow-initiation delay</u>
t_2 = <u>full-flow delay</u>

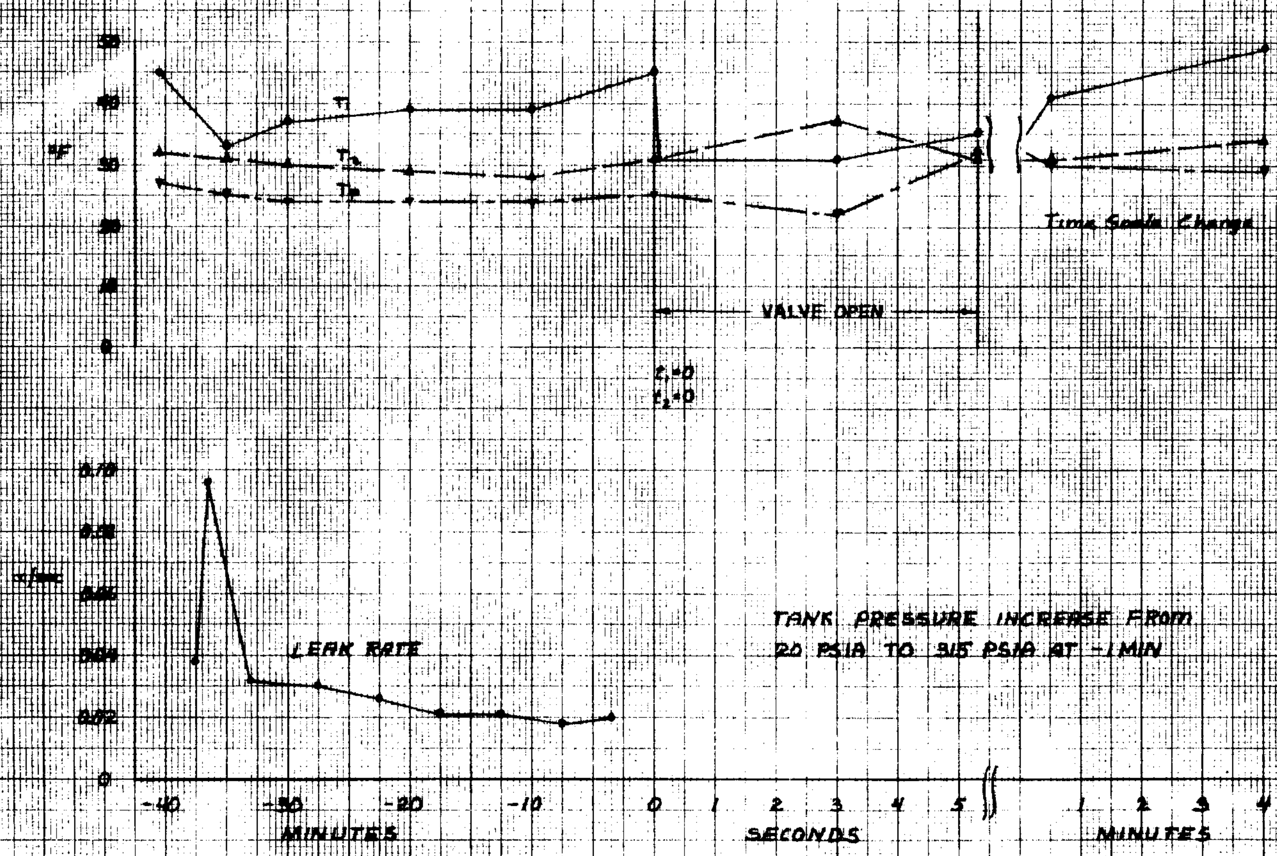
All of the leak data reported here was obtained according to the procedure discussed in Section 4.3.3 except for Run I-46. That test is divided into three parts labeled A, B, and C. At the start of the test, the leak rate was adjusted to a sufficiently large level that considerable accumulation of frozen N_2O_4 occurred in the combustion chamber. The oxidizer valve was opened when the solid material appeared to fill the chamber. After a few seconds, the valve was closed and the leaking process was allowed to continue. This procedure was followed for three full openings of the valve and differs from the standard procedure where the flow system downstream from the propellant valve was thoroughly purged prior to each test.

I-18

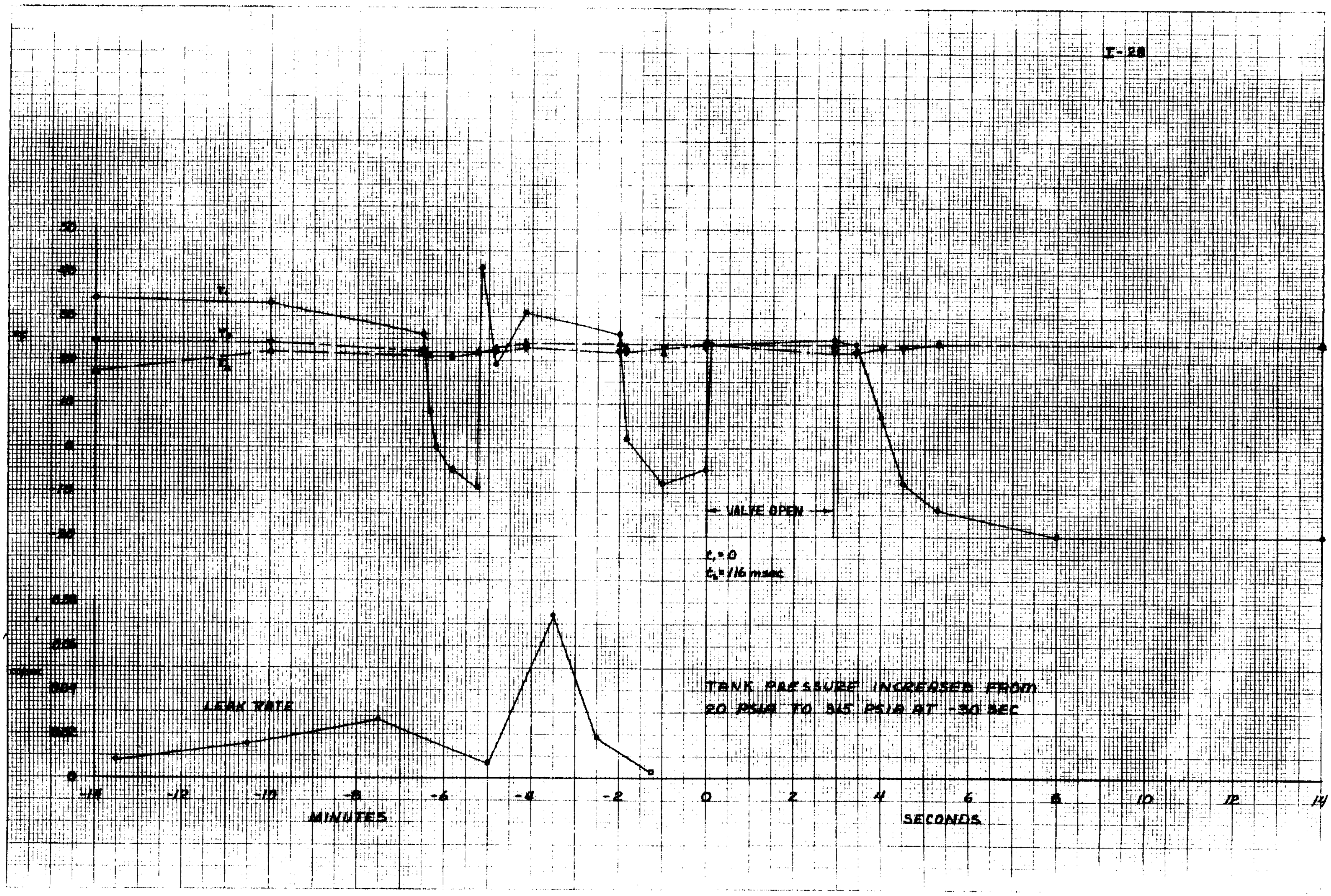


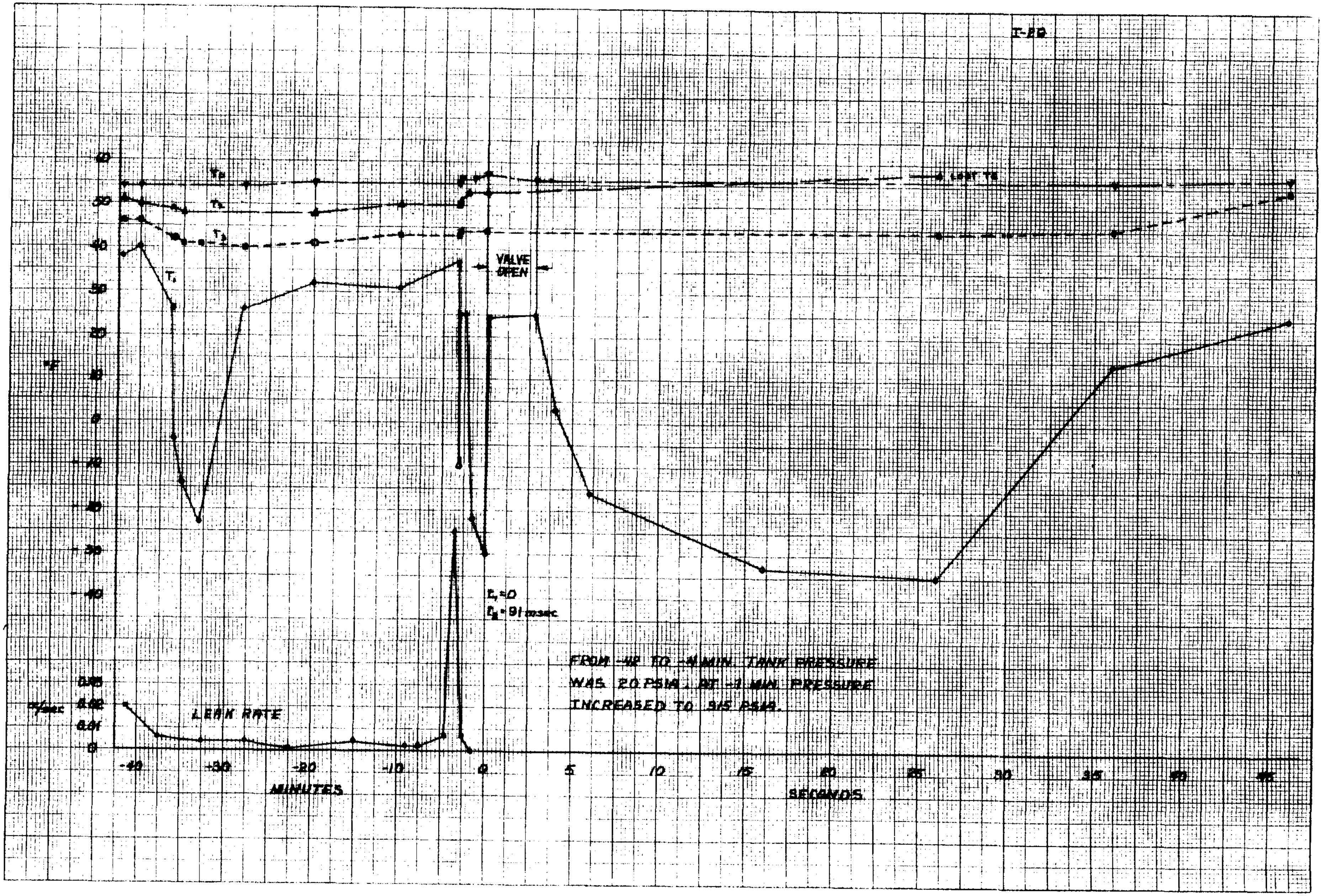
60
50
40
°F 30
20
10
0
-10
T_1
T_2
t_1 = 16 msec
t_2 = 76 msec
0.02
cc/sec
0.01
0
LEAK RATE
-50
-40
-30
-20
-10
0
2
4
6
8
10
12
14
16
18
MINUTES
SECONDS


I-26
T₁
T₂
T₃
°F
50
40
30
20
10
0
0.10
0.08
0.06
0.04
0.02
0
LEAK RATE
VALVE OPEN TIME
NOT RECORDED
TANK PRESSURE INCREASED FROM
20 PSIA TO 515 PSIA AT -3 MIN
-35
-30
-25
-20
-15
-10
-5
0
1
2
MINUTES
SECONDS

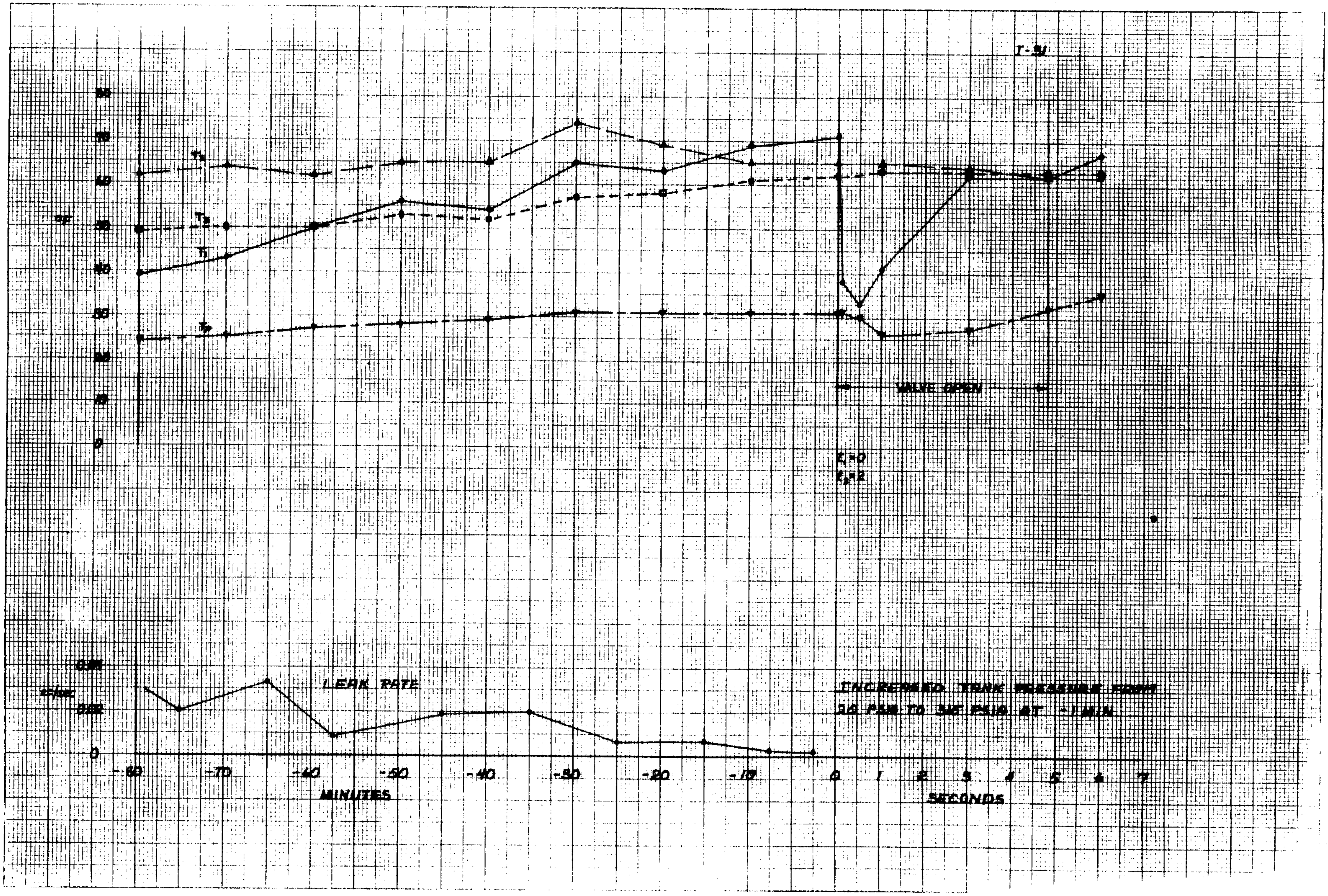


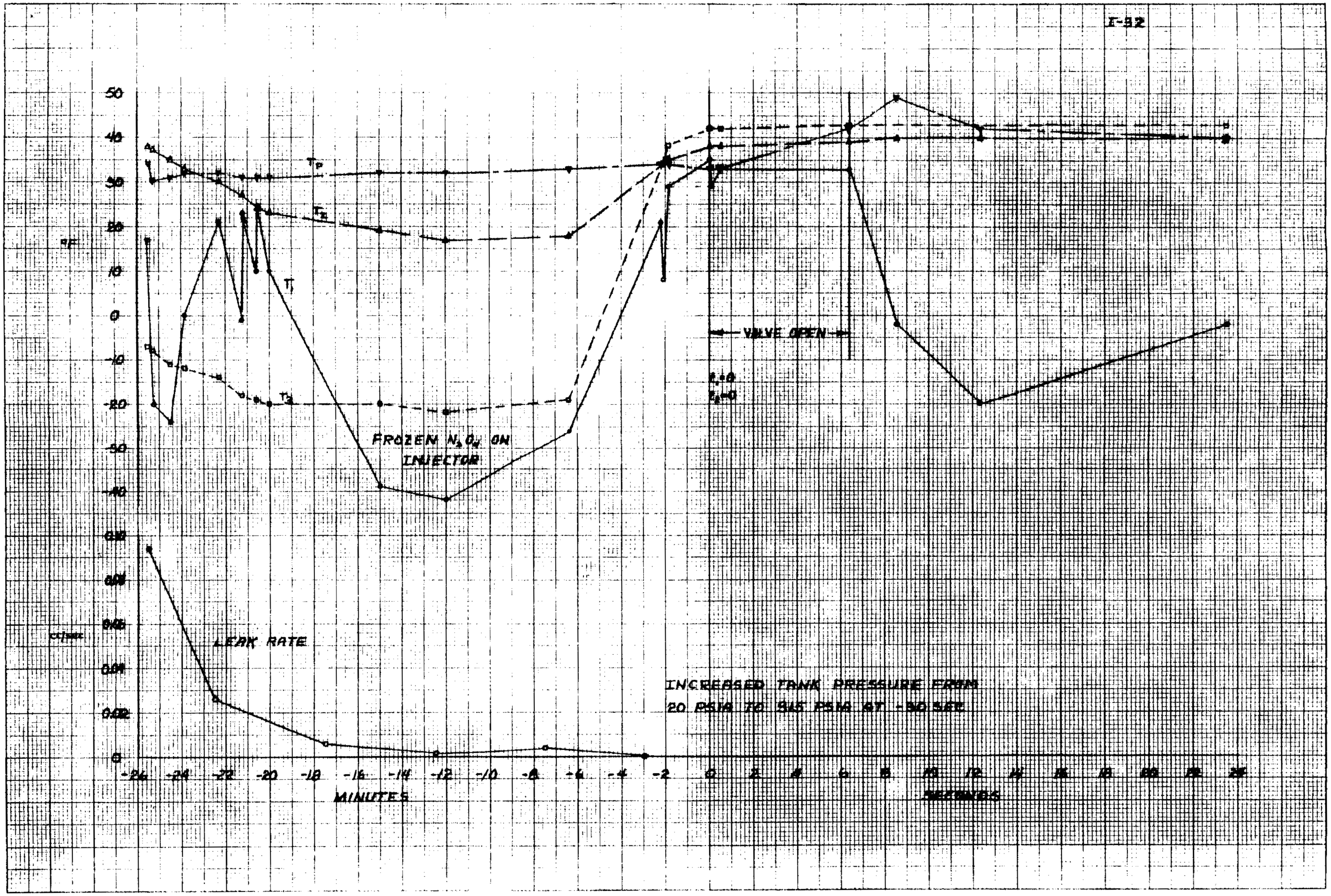
°F
50
40
30
20
10
0
T_1
T_a
T_B
VALVE OPEN
$t_1 = 0$
$t_2 = 0$
Time Scale Change
0.70
0.02
0
LEAK RATE
TANK PRESSURE INCREASE FROM
20 PSIA TO 315 PSIA AT -1 MIN
-40
-30
-20
-10
0
1
2
3
4
5
MINUTES
SECONDS

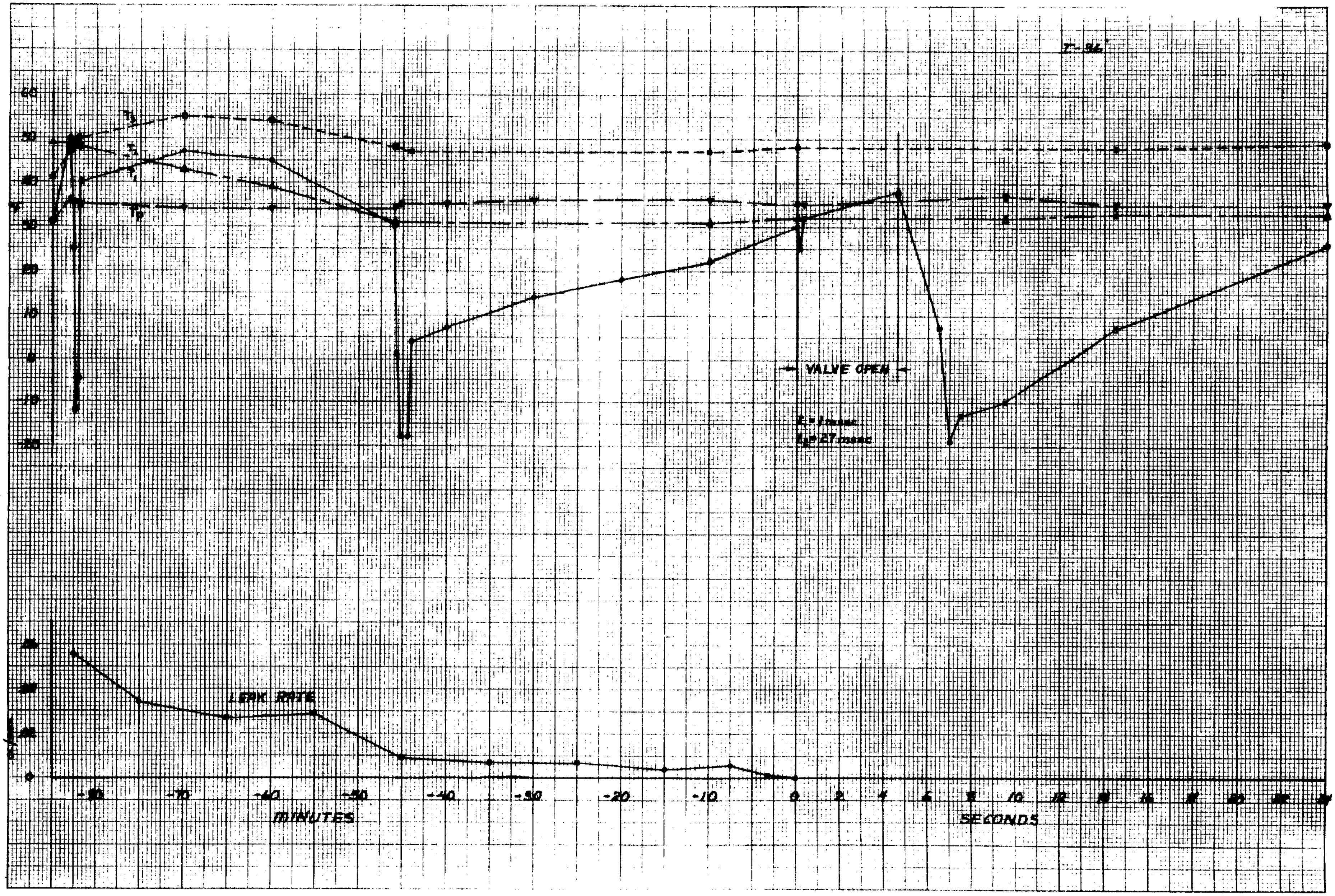

I-28
VALVE OPEN
$t_1 = 0$
$t_2 = 116$ msec
TANK PRESSURE INCREASED FROM
20 PSIA TO 315 PSIA AT -30 SEC
LEAK RATE
MINUTES
SECONDS

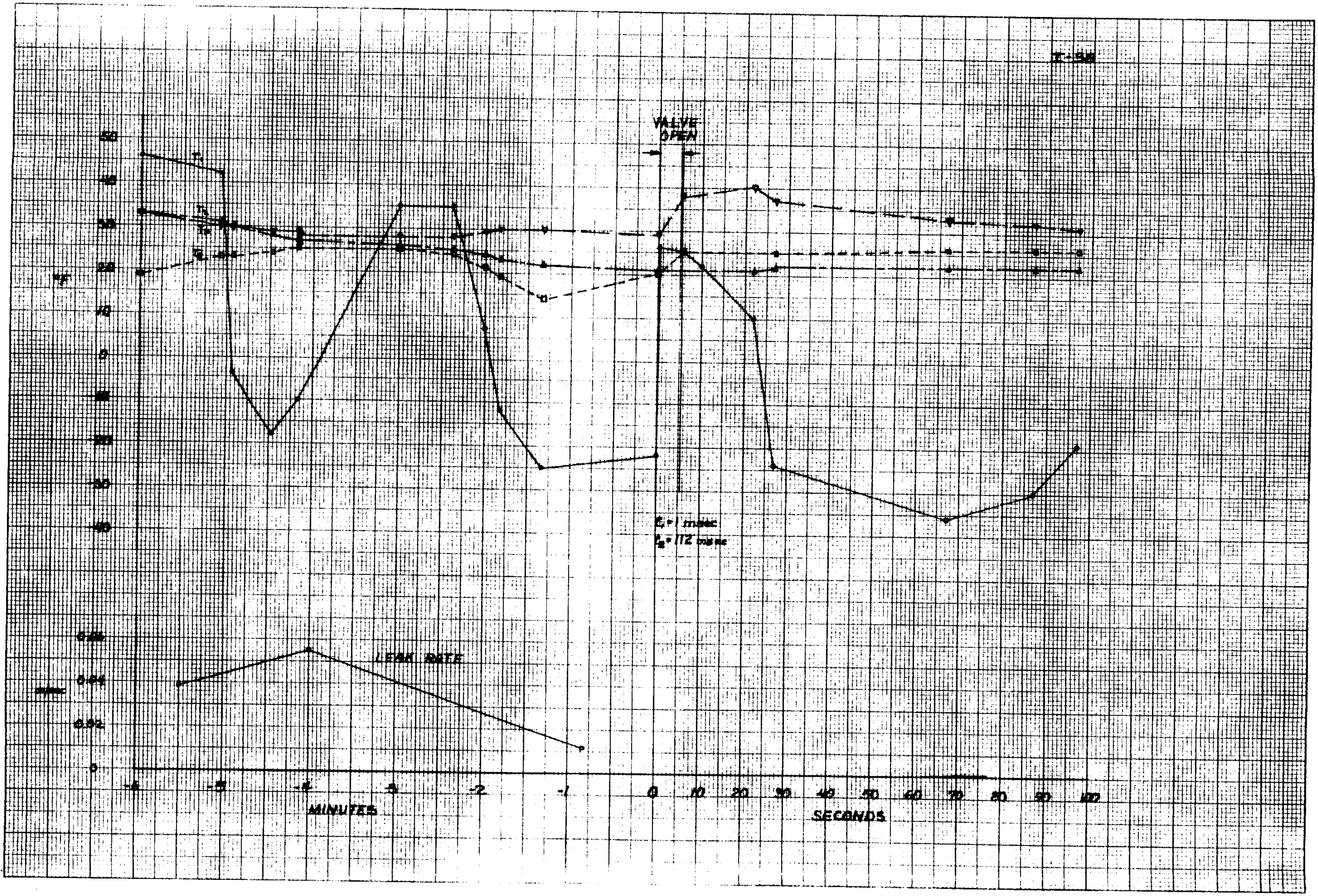


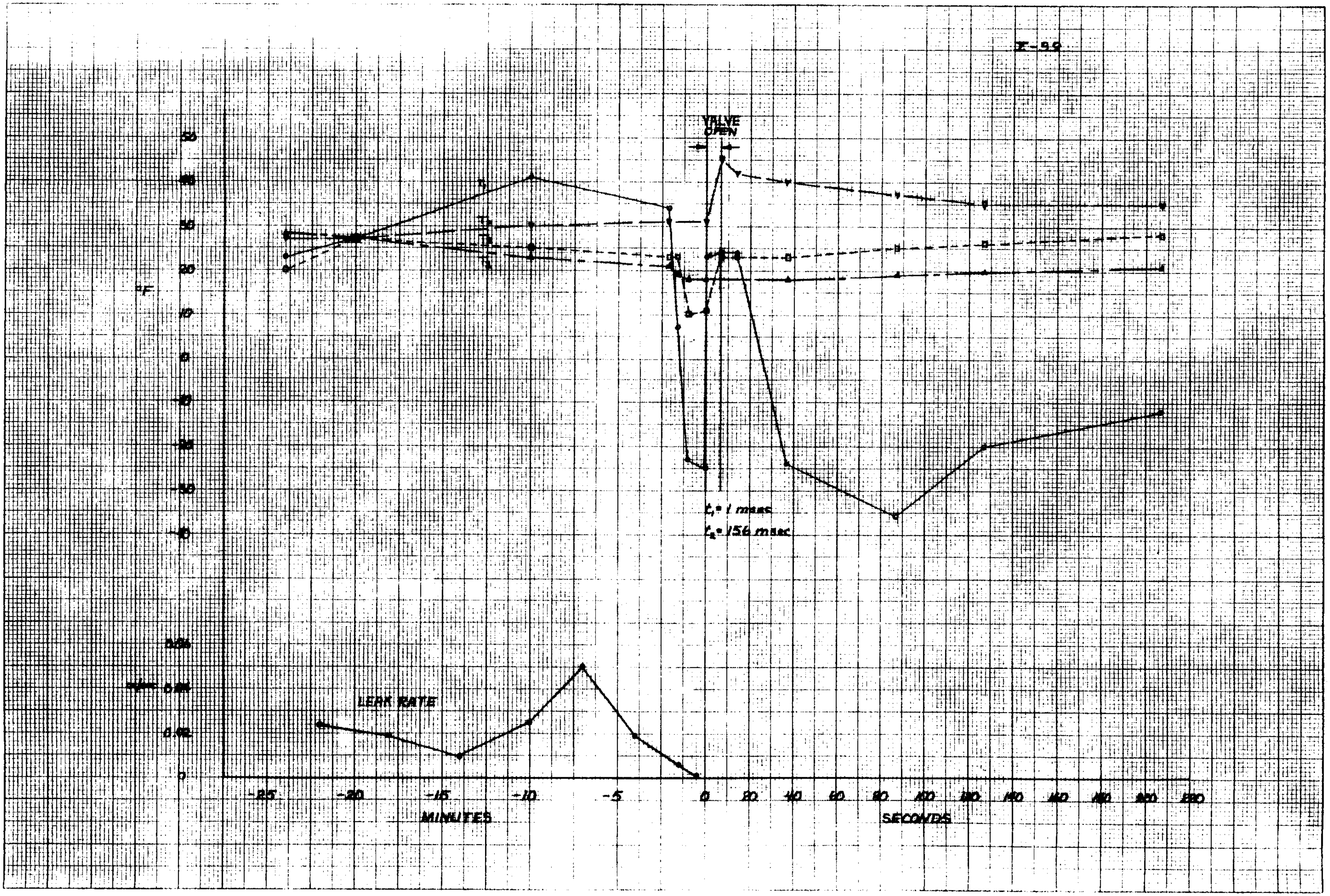
I-29
°F
#/sec
LEAK RATE
VALVE OPEN
$T_1 = 0$
$T_2 = 91$ msec
FROM -42 TO -4 MIN. TANK PRESSURE
WAS 20 PSIA; AT -1 MIN. PRESSURE
INCREASED TO 315 PSIA.
MINUTES
SECONDS


I-31
VALVE OPEN
LEAK RATE
MINUTES
SECONDS
INCREASED TANK
AT -1 MIN.

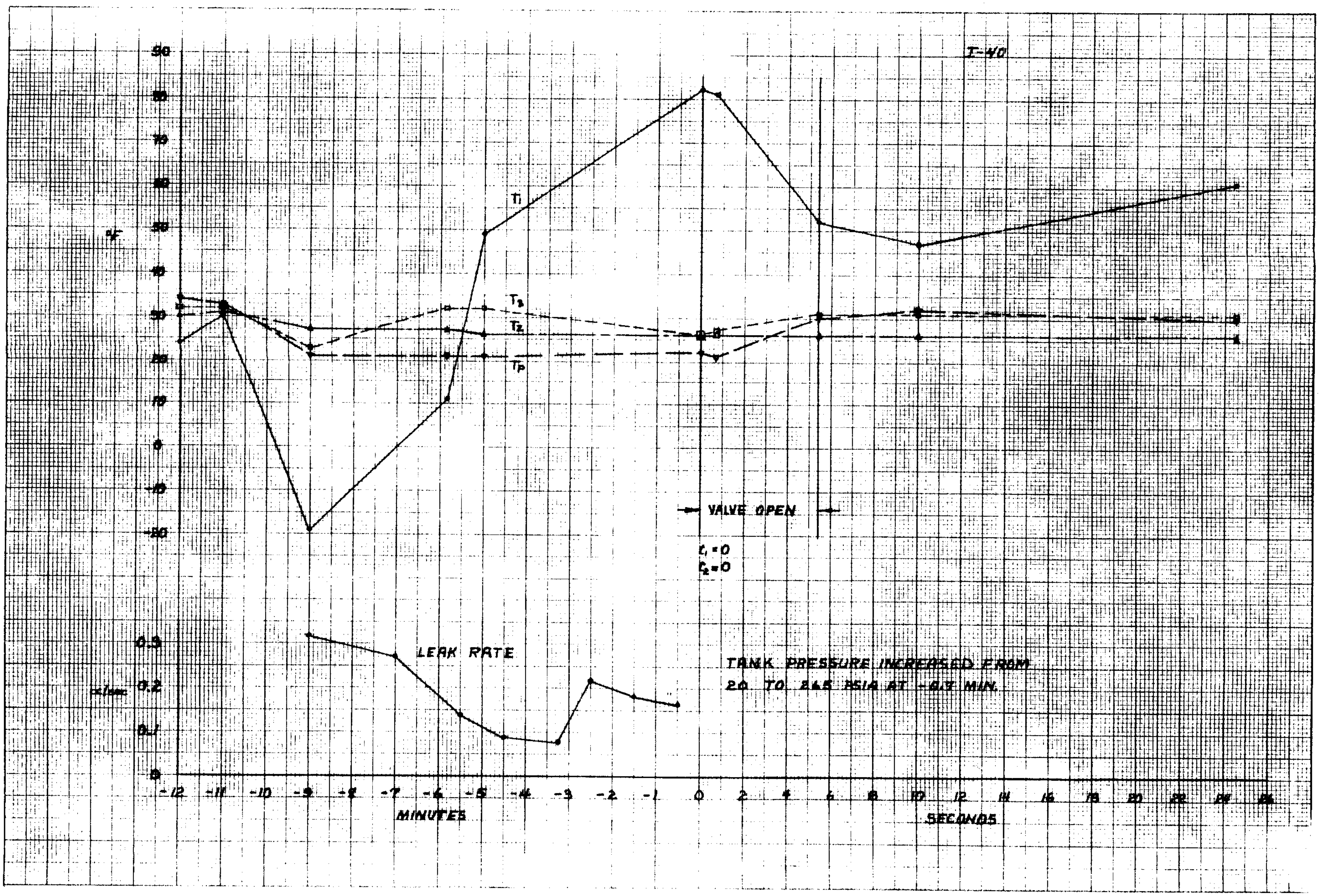

I-32
°F
cc/sec
LEAK RATE
FROZEN N_2O_4 ON INJECTOR
VALVE OPEN
INCREASED TANK PRESSURE FROM
20 PSIA TO 315 PSIA AT -30 SEC
MINUTES
SECONDS

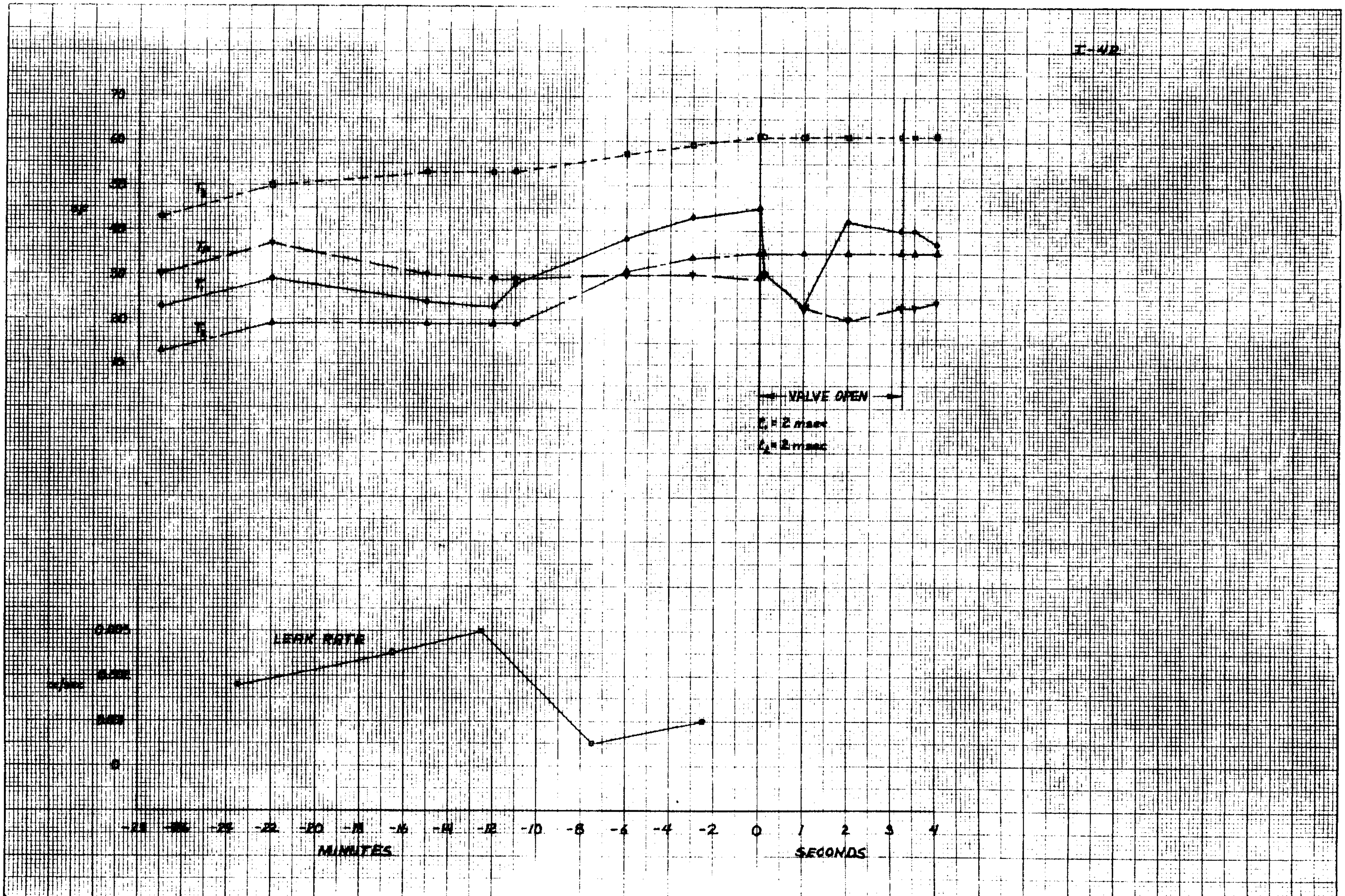

T-36
VALVE OPEN
LEAK RATE
MINUTES
SECONDS


VALVE OPEN
°F
LEAK RATE
MINUTES
SECONDS
0
10
20
30
40
50
60
70
80
90
100

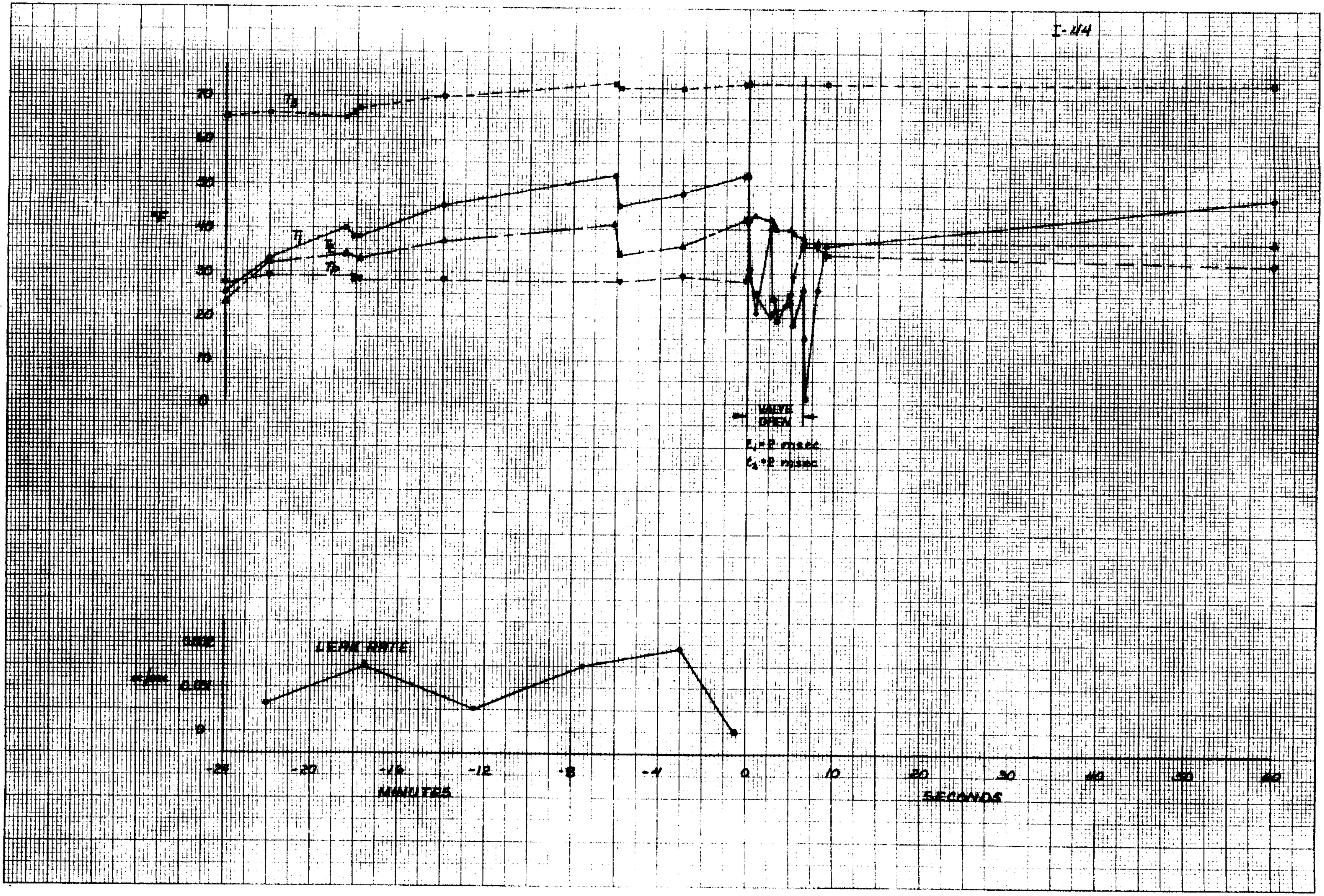


VALVE OPEN
°F
t_1 = 1 msec
t_2 = 156 msec
LEAK RATE
MINUTES
SECONDS

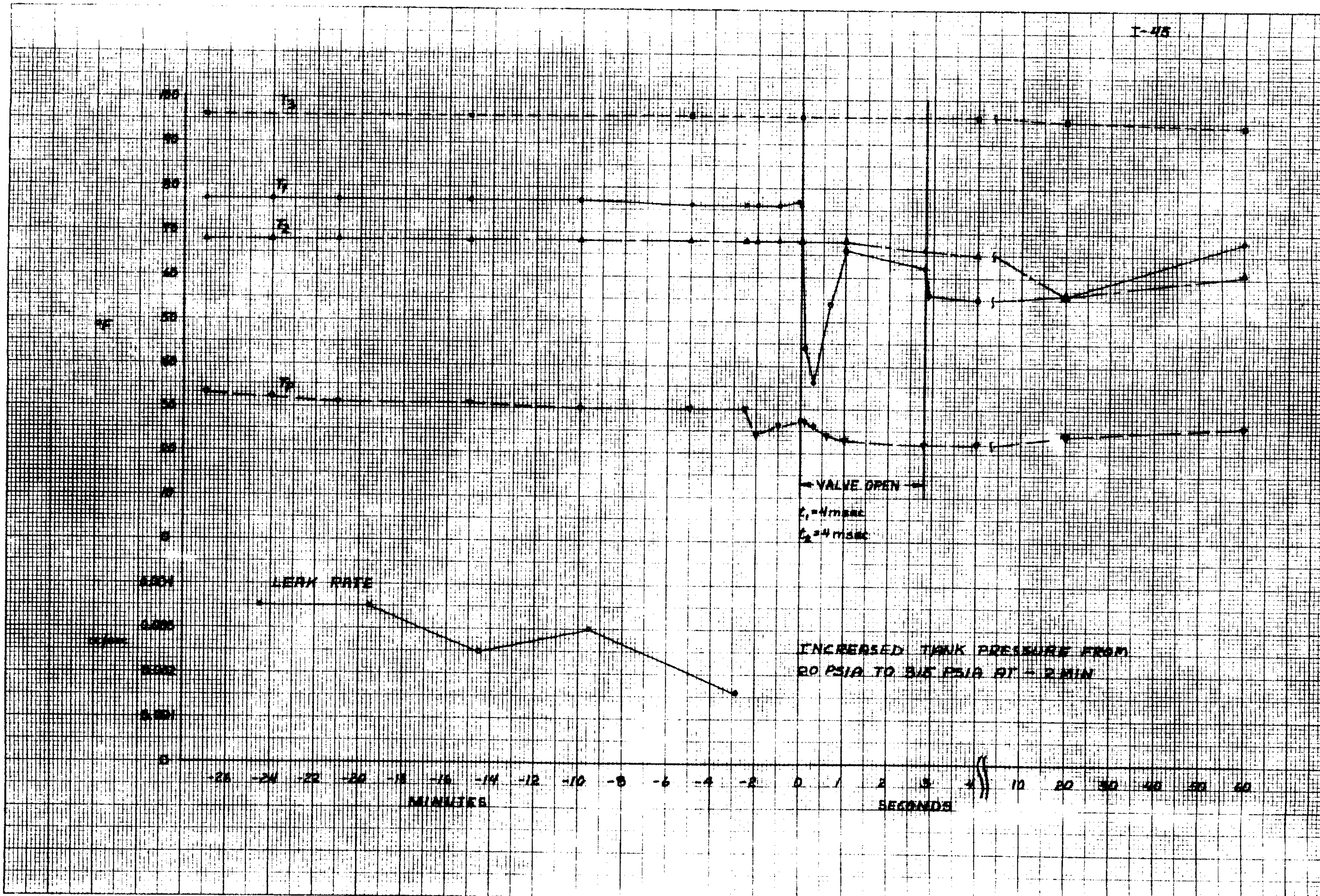

T-40
°F
cc/sec
T1
T3
T2
TP
VALVE OPEN
t1 = 0
t2 = 0
LEAK RATE
TANK PRESSURE INCREASED FROM
20 TO 24.5 PSIA AT -8.7 MIN.
MINUTES
SECONDS


I-42
70
60
50
40
30
20
10
°F
VALVE OPEN
LEAK RATE
0
-10
-8
-6
-4
-2
0
1
2
3
4
MINUTES
SECONDS

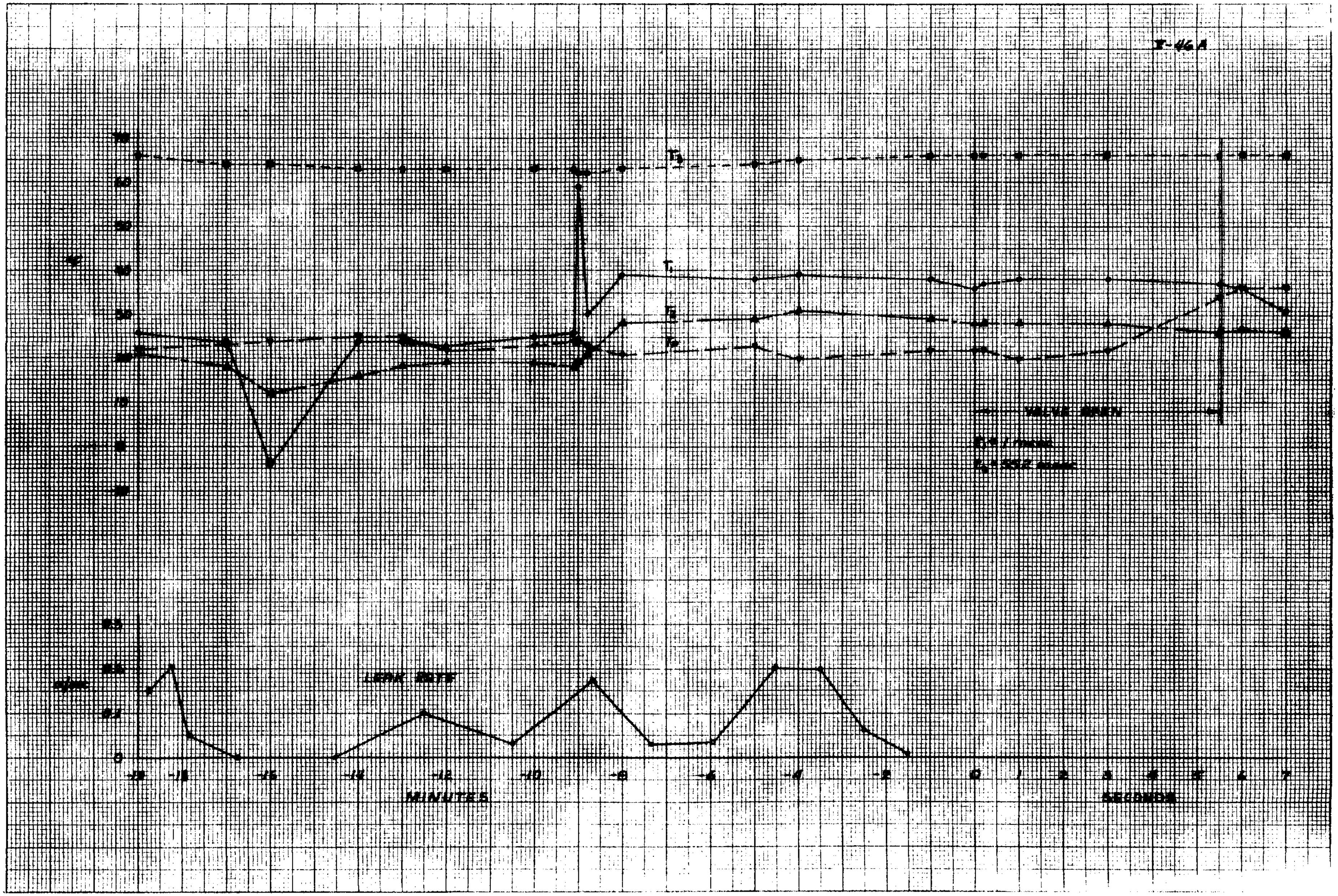
I-114

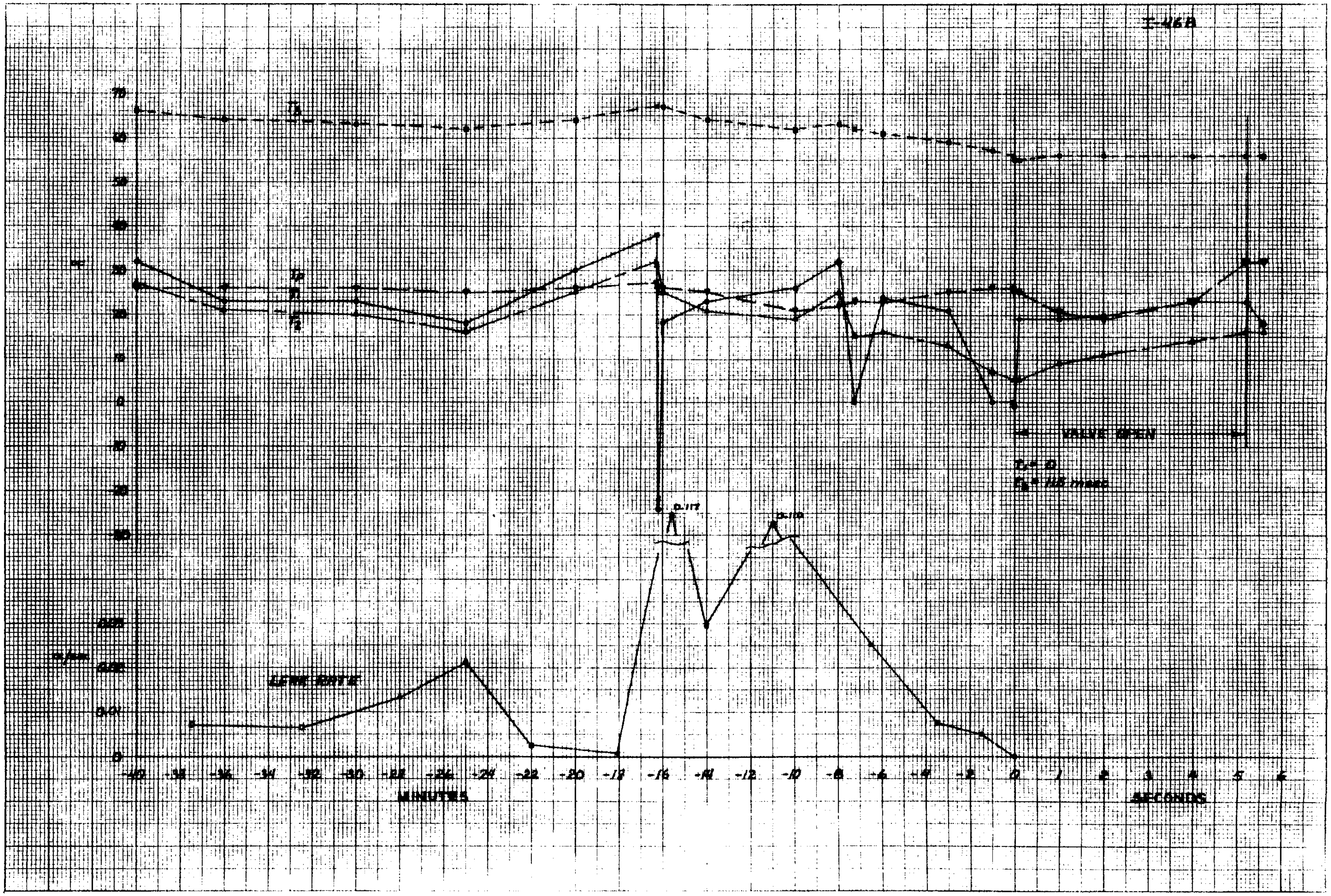


°F
70
60
50
40
30
20
10
0
T_3
T_1
T_2
T_B
VALVE OPEN
$t_1 = 2$ msec
$t_4 = 2$ msec
LEAK RATE
0.02
0.01
0
-24
-20
-16
-12
-8
-4
0
10
20
30
40
50
60
MINUTES
SECONDS

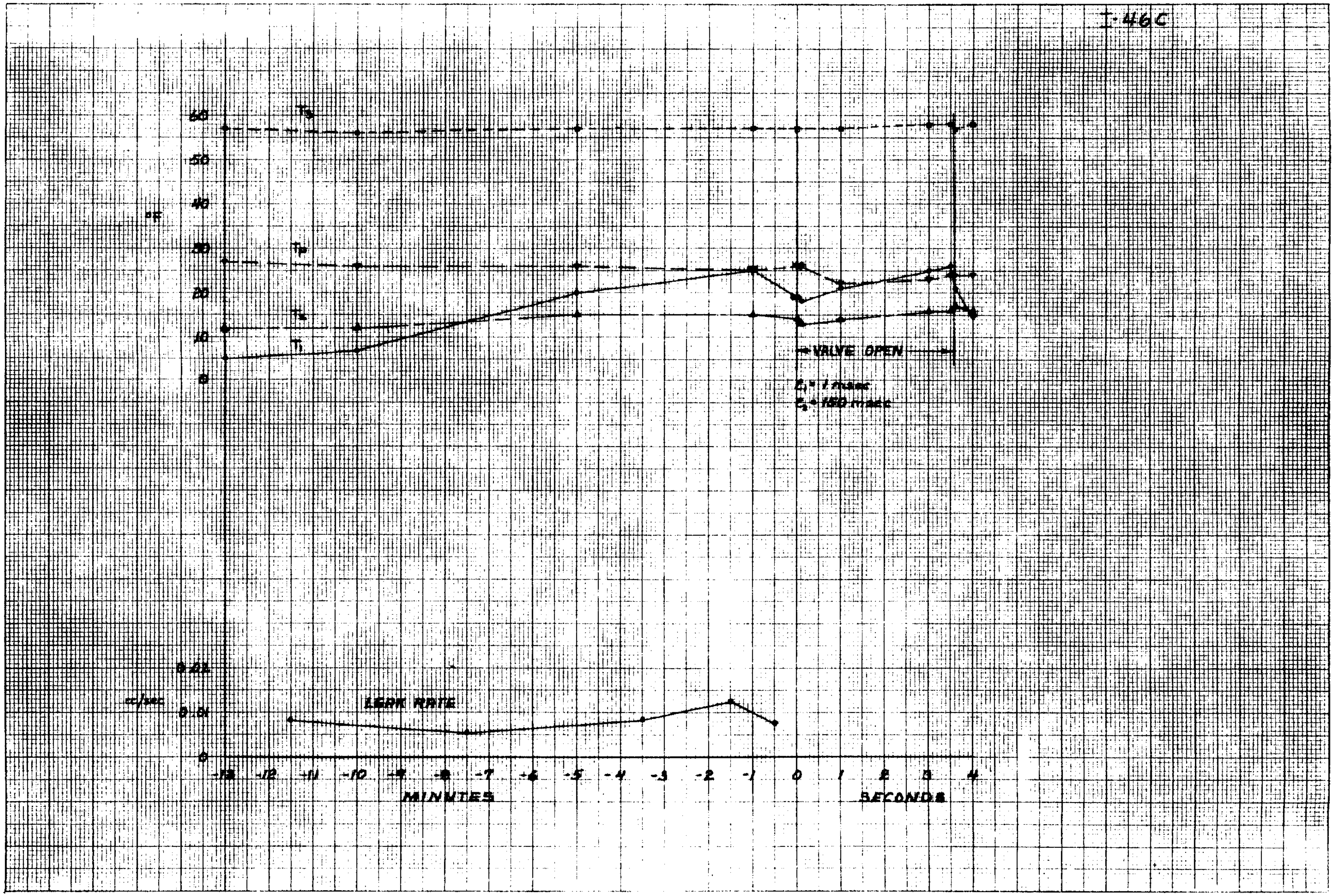


T_3
T_1
T_2
T_F
°F
100
90
80
70
60
50
40
30
20
10
0
LEAK RATE
0.004
0.003
0.002
0.001
0
← VALVE OPEN →
t_1 = 4 msec
t_2 = 4 msec
INCREASED TANK PRESSURE FROM
20 PSIA TO 315 PSIA AT − 2 MIN
-26
-24
-22
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
1
2
3
4
10
20
30
40
50
60
MINUTES
SECONDS

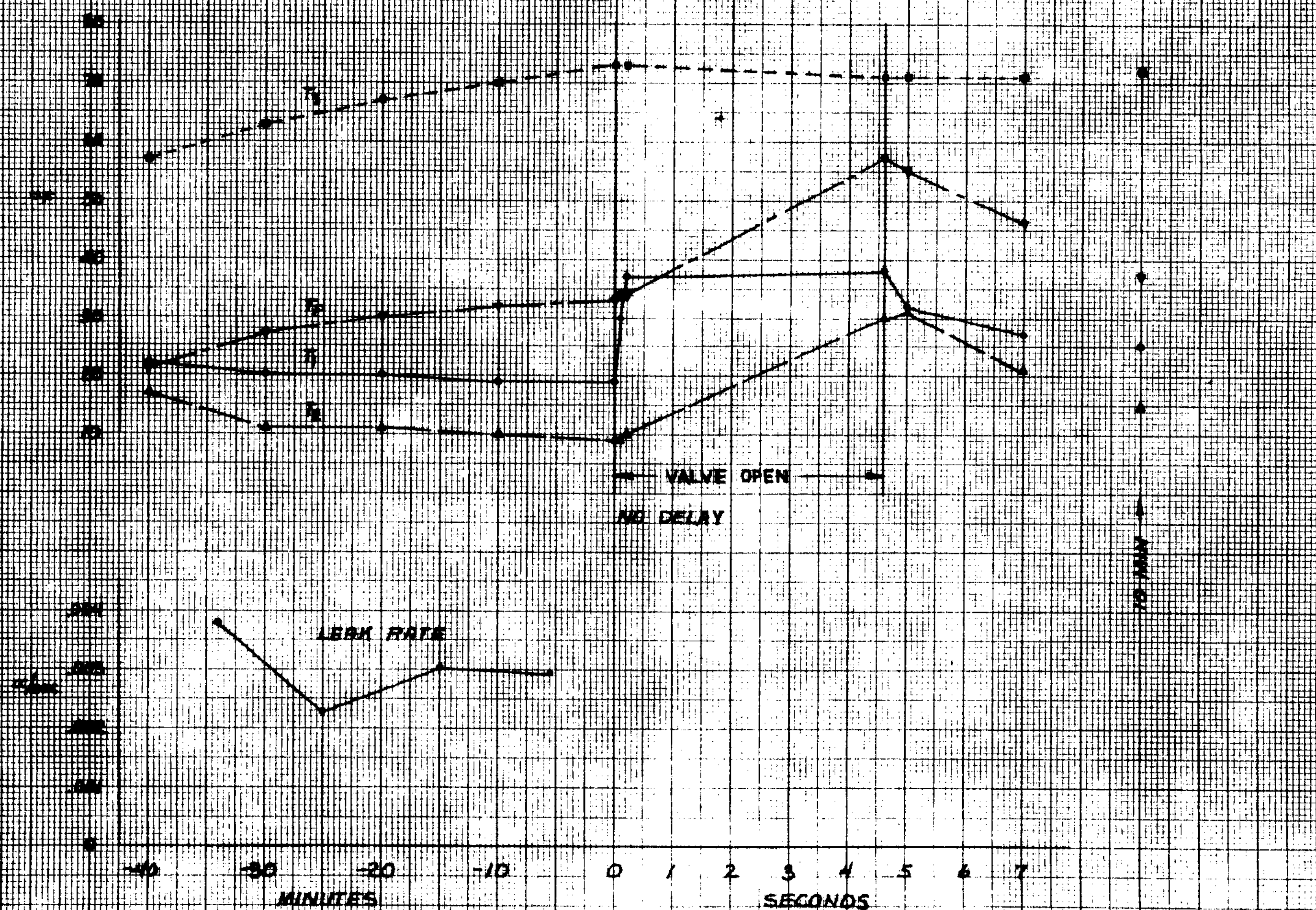

X-46A
VALVE OPEN
LEAK RATE
MINUTES
SECONDS

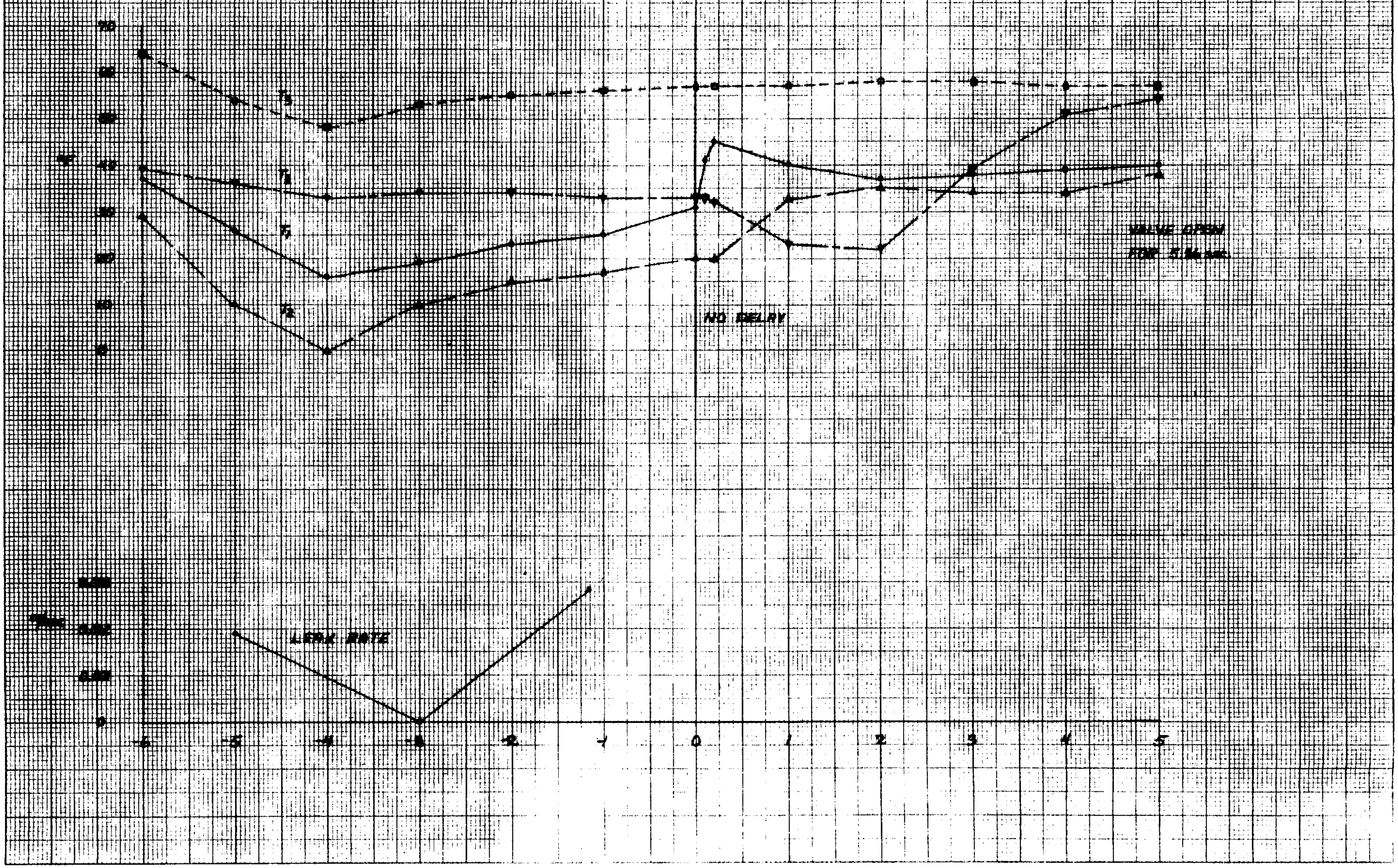


I-46B
VALVE OPEN
LEAK RATE
MINUTES
SECONDS

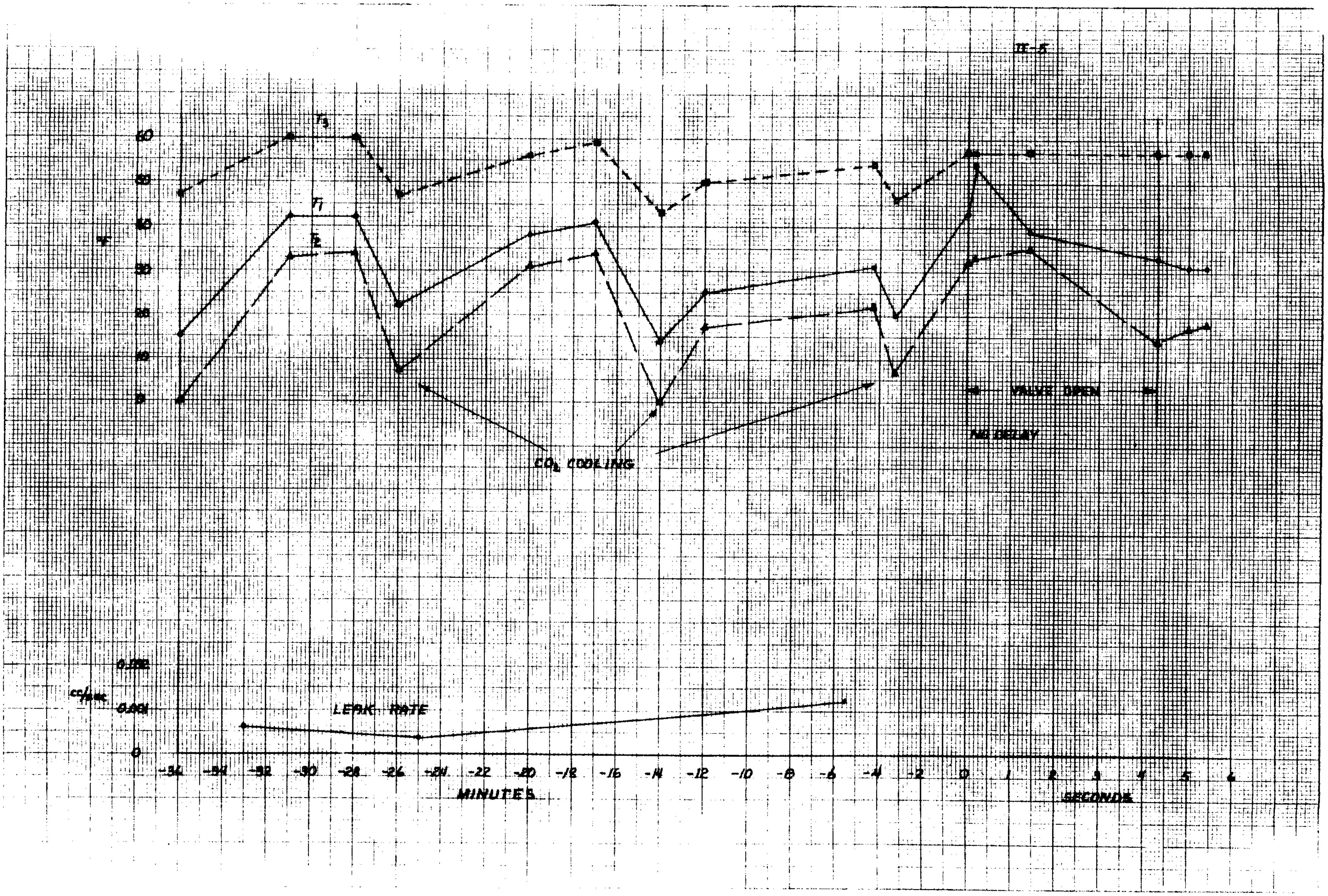


I-46C
60
50
40
°F
30
20
10
0
T_S
T_P
T_A
T_I
VALVE OPEN
t_1 = 1 msec
t_2 = 150 msec
0.02
cc/sec
0.01
0
LEAK RATE
-13
-12
-11
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
MINUTES
SECONDS


VALVE OPEN
NO DELAY
LEAK RATE
MINUTES
SECONDS
10 MIN



70
60
50
40
30
20
10
°C
T_3
T_4
T_1
T_2
VALVE OPEN
NO DELAY
LEAK RATE
0
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5


II-5
T_3
T_1
T_2
°F
VALVE OPEN
NO DELAY
CO_2 COOLING
LEAK RATE
cc/sec
MINUTES
SECONDS